FATIGUE AND RECOVERY DURING TASKS WITH COMPLEX FORCE PATTERNS

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TITLE: Fatigue And Recovery During Tasks With Complex Force Patterns

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ABSTRACT

The purpose of this thesis was to improve our understanding of the progression of fatigue and recovery during repetitive work and to examine selected methods for predicting fatigue. In Chapter 2, a psychophysical methodology was used to validate the Maximum Acceptable Effort (MAE) equation of Potvin (2012) at duty cycles of greater than 0.5. The results from that study were used to evaluate the MAE equation in the higher duty cycle range. In Chapter 3, the fatigue process during complex MVC-relative force profiles was examined in a repetitive handgrip task. In Chapter 4, I examined the effect of manipulating the order of presentation of various MVC-relative force levels for a repetitive thumb flexion task. Additionally, the influence of post-activation potentiation was examined by stimulating the flexor pollicis longus (FPL) at specific time points during the complex profile. In Chapter 5, Xia and Frey Law's (2008) three-compartment model ($3CM_{XFL}$) of muscle fatigue was modified to more accurately reflect physiological processes. The model, with physiological modifications ($3CM_{GMU}$), as well as the original 3CM optimized for complex tasks ($3CM_{OPT}$), was optimized to predict the fatigue levels from the experiments described in Chapters 3 and 4, as well as 4 other similar experimental protocols. The predicted fatigue from the $3CM_{XFL}$ was also compared to the experimental data. The $3CM_{OPT}$ and $3CM_{GMU}$ were compared against known endurance times. The $3CM_{GMU}$ is proposed as an ergonomic tool for evaluating fatigue in repetitive tasks, and the future directions for fatigue modelling and using the MAE equation for complex force-time histories are addressed.

This thesis provides the first studies of fatigue accumulation during complex MVC-relative time histories. The findings from this thesis can be applied to the workplace to reduce the risk of injury as a result of muscle fatigue.

Keywords: Psychophysics, muscle fatigue, complex MVC-relative time history, fatigue modelling.

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THESIS FORMAT AND ORGANIZATION

This thesis contains material from the PhD work of Michael W.L. Sonne and has been prepared in a “sandwich” format as outlined in the McMaster University School of Graduate Studies’ Guide for the Preparation of Thesis. The thesis begins with an introductory chapter (Chapter 1), followed by a description of 4 studies that have been prepared as separate manuscripts (Chapters 2 – 5). The thesis ends with a concluding chapter (Chapter 6), which discusses the findings of the thesis as a whole, and provides applications and future directions for similar research.

CONTRIBUTIONS TO PAPERS WITH MULTIPLE AUTHORS

Chapter 2 – Published in "Ergonomics", September, 2014.

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Contributions

Chapter 2 has been published in *Ergonomics*. This study was the work and conception of Michael W.L. Sonne and Dr. Jim R. Potvin. Both co-authors contributed to this chapter. The development of the methodology, data collection, analysis, interpretation and manuscript preparation was performed by Michael Sonne. Dr. Potvin was a significant contributor to the conception of the work, development of the methodology, data interpretation, and manuscript preparation.

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Contributions

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Chapter 5 – Formatted for Publication

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CHAPTER 1: INTRODUCTION

1.1.1 WHAT IS MUSCLE FATIGUE AND WHY IS IT AN ISSUE IN ERGONOMICS?

Muscle fatigue reduces force output, may lead to discomfort and pain, and has been related to musculoskeletal disorders in the workplace (Chaffin, Andersson, & Martin, 2006). Fatigue has been defined as "*the exercise-induced reduction in the ability of the muscle to produce force or power, whether or not the task can be sustained*" (Enoka & Duchateau, 2008). It is the gradual process in which maximum force or power is reduced, not the point where task failure occurs. The muscle fatigue process starts soon after the onset of a muscle contraction, and the rate of fatigue is affected by many factors (Enoka & Duchateau, 2008).

Muscle fatigue is associated with changes in the concentration of intracellular metabolites (Bigland-Ritchie & Woods, 1984), and is highly related to decreases in sensitivity of the muscle fibres to Ca^{2+} (Moopanar & Allen, 2005), thus reducing the number of cross bridge cycles that can be initiated, and decreasing the overall muscle tension (Søgaard, Orizio, & Sjøgaard, 2006). However, during endurance exercise, depletion of muscle glycogen stores occurs, preventing the synthesis of ATP, resulting in a consequent failure to release calcium to begin the contraction process. In endurance type activities, muscle fatigue has also been shown to have long lasting effects, with the byproducts of fatigue (such as blood metabolite concentrations as well as diminished force production) existing up to 48 hours after a bout of exercise (Yung et al., 2012). Fatigue accumulates at a rapid rate during intense contractions, but the fatigue rate drops exponentially as muscular intensity decreases (El ahrache, Imbeau, & Farbos, 2006; Frey Law & Avin, 2010; Rohmert, 1973).

The fatigue process is a concern when designing the workplace, as tasks that may be acceptable when completed infrequently, may cause muscle fatigue when performed more repetitively. Tasks that once were acceptable, based on strength capacities for unfatigued workers, may now exceed the muscular strength limits for workers who are fatigued. For ergonomists, it is important to properly quantify the fatigue response to properly accommodate workers, and prevent workplace injury.

1.1.2 LIMITATIONS IN EVALUATING JOBS THAT MAY BE FATIGUING

Rohmert (1973) developed a commonly used equation to determine acceptable rest allowances (RA) for intermittent muscle contractions (Equation 1).

$$RA = 18 * (Holding\ Time) * (\frac{Holding\ Time}{Endurance\ Time})^{1.4} * \sqrt{\frac{Joint\ Moment}{Joint\ Strength} - 0.15} \quad [1]$$

Where: holding time is the amount of time (in seconds) that the task is being performed, endurance time is the maximum amount of time that a contraction can be held for the given effort level, joint moment is the current demand on the muscles causing the moment, and joint strength is the maximum moment that can be developed by that joint in that position.

One major limitation of this method is the assumption that, for tasks below 15% of maximum voluntary contraction (MVC), there is no need for rest. Multiple studies have since refuted these findings (Björkstén & Jonsson, 1977; Oude Vrielink, Huub & Van Dieen, 1996). For prolonged, static holding tasks, fatigue onset has been shown to occur at efforts as low as 2.6% of maximum voluntary contraction (MVC) (Hagberg, 1981), ranging up to 8% MVC (Byström & Fransson-Hall, 1994; Byström & Kilbom, 1990). Evidence of fatigue was seen during tasks of 5% MVC after 4 hours (Oude Vrielink, Huub & Van Dieen, 1996). Fatigue has also been shown to occur at 7.9% of MVE during sustained isometric contractions of the elbow flexors (Björkstén & Jonsson, 1977) and at 5% of MVE during sustained contractions of the knee flexors (Sjøgaard, Kiens, Jørgensen, & Saltin, 1986). Physiological evidence of fatigue was observed between 5% and 10% of MVE during various continuous isometric tasks (Jørgensen, Fallentin, Krogh-Lund, & Jensen, 1988).

Secondly, Rohmert's equation (1973) was developed to evaluate efforts that were either sustained isotonic, or intermittent isotonic followed by rest periods (ie. on/off) (Rohmert, 1973). While such tasks do occur in industry, assembly line tasks typically consist of intermittent demands with complex force histories. In studies involving intermittent tasks, participants have typically been asked to perform exertions at a given percentage of their rested MVC (termed "MVC-relative" in this thesis) for an allotted amount of time, followed by some regular period of absolute rest. There has been little research conducted to examine how fatigue accumulates during tasks where there is no period of absolute rest and force histories are complex in nature, though initial investigations have been undertaken (Wells, Sonne, & Potvin, 2012; Yung & Wells, 2012).

1.1.3 IMPROVED METHOD IN IDENTIFYING ACCEPTABLE EFFORTS IN STEREOTYPICAL REPETITIVE TASKS

Kilbom (1994) described the active proportion of work periods throughout the course of a task as the “Duty Cycle” (Equation 2).

$$Duty\ Cycle = \frac{Work}{Work + Rest} \quad [2]$$

Where work is the period of time where the muscle is activated and performing the task, and rest is the period of time where there is no muscular activation required (Kilbom, 1994). More recently, Potvin (2012) developed an equation to predict maximum acceptable efforts based on duty cycle. He selected maximum acceptable effort (MAE) data from psychophysical studies that fell within a strict set of inclusion criteria. The maximum acceptable effort refers to the average maximum acceptable force or torque expressed as a percentage of the maximum force or torque from a maximum voluntary contraction (MVC) for a specific task (Potvin, 2012). The studies, used to develop the equation, required participants to receive extensive training on the task prior to data collection, as well as having the training and testing on separate days. However, there was only one experiment that examined duty cycles of greater than 0.50 (Moore & Wells, 2005). Given the relative lack of psychophysical data for high duty cycle tasks, data from physiological studies were used to support MAE values for these tasks (Björkstén & Jonsson, 1977; Byström & Fransson-Hall, 1994; Byström & Kilbom, 1990; Jorgensen, Fallentin, Krogh-lund, & Jensen, 1988; Sjøgaard et al., 1986).

Potvin (2012) determined that only duty cycle was required to accurately predict the MAE using a stepwise regression analysis, and that duty cycle was a much better predictor than frequency. An R^2 value of 0.87 was established between the equation and the experimentally determined MAE values, with an RMS error of 7.2% MVC. The shape of the curve, represented by the equation, predicts that acceptable effort levels decrease to as low as 2% of MVC when at a duty cycle of 90% (Figure 1.1). This level is well below the limits initially assumed to be acceptable by Rohmert (1973), further supporting the need for more modern tools when analyzing fatiguing tasks in the workplace. A limitation of Potvin’s MAE equation is the lack of extensive psychophysical data in the high duty cycle range of the equation, with only one study representing MAEs above a duty cycle of 0.50 as Moore & Wells, (2005) tested at 0.85.

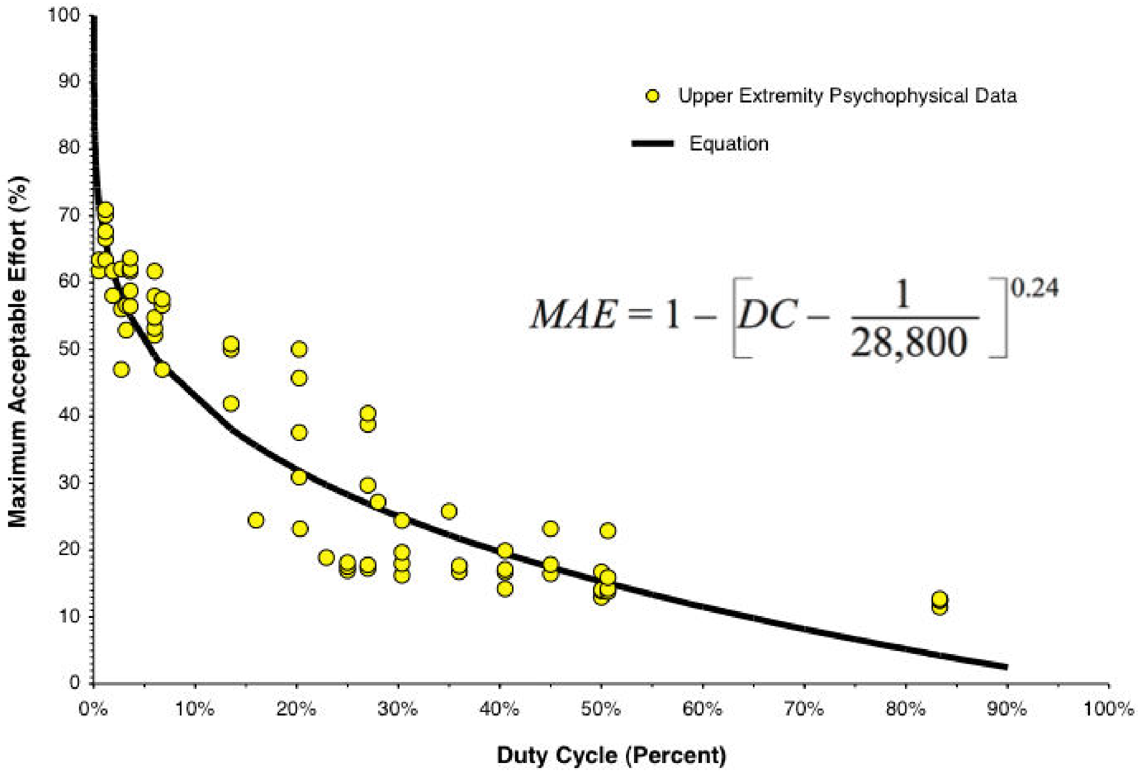

Figure 1.1. The MAE equation from Potvin (2011)(inset) compared against maximum acceptable efforts from psychophysical experiments using duty cycles between 0.01 and 0.85. An analysis of 69 different psychophysical values from 7 different studies were used, resulting in an r^2 of 0.87, and an RMS difference of 7.2% MVC. The curve ends at a duty cycle of 0.9, as it is unlikely that an ergonomist will ever come across a repetitive task where the product of frequency and effort duration comes close to this level, let alone surpasses it. In the equation, the 28,800 represents the number of seconds in an 8 hour work day, such that 100% MVC can be performed for 1 second per day.

1.1.4 FATIGUE ACCUMULATION DURING COMPLEX TIME HISTORIES

One particular limitation of most fatigue research and its application to industrial tasks is the use of force profiles which are both isotonic and sustained, or off/on between 0% and efforts of the same intensity (i.e., 30%, 0%, 30%, 0%). In many industrial tasks, it is uncommon for the worker to be able to completely rest and, typically, they have to move on to another task in order to complete the cycle (Iridiastadi & Nussbaum, 2006). Yung et al., (2012) conducted a series of experiments to determine the effects of varying force amplitude on the fatigue response. Using a battery of fatigue evaluation methods, including EMG, mechanomyography, blood chemistry levels and stimulated force production, the researchers examined a continuum of tasks that all had an average demand of

15% MVC. On the most fatiguing end of the spectrum was a continuously isotonic contraction, where the participants held a triceps extension task at 15% of their MVC until exhaustion. On the opposite end of the spectrum, participants performed a 30% MVC for 5 seconds, then received a 5 second rest period. The three other force patterns were as follows: a sinusoidal pattern from 0 to 30% MVC, with peaks occurring every 6 seconds and an average force of 15% MVC (sinusoidal); a pattern where participants held 29% MVC for 3 seconds, followed by 1% MVC for 3 seconds (1 percent); a pattern with 22.5% MVC for 3 seconds, then 7.5% MVC for 3 seconds (MinMax) (Figure 1.2). The 1 percent condition was found to be slightly less fatiguing than the on/off condition (as measured by the number of statistically significant fatigue measures), with the MinMax condition being less fatiguing than the isometric condition, but more fatiguing than the sinusoidal pattern (Figure 1.2).

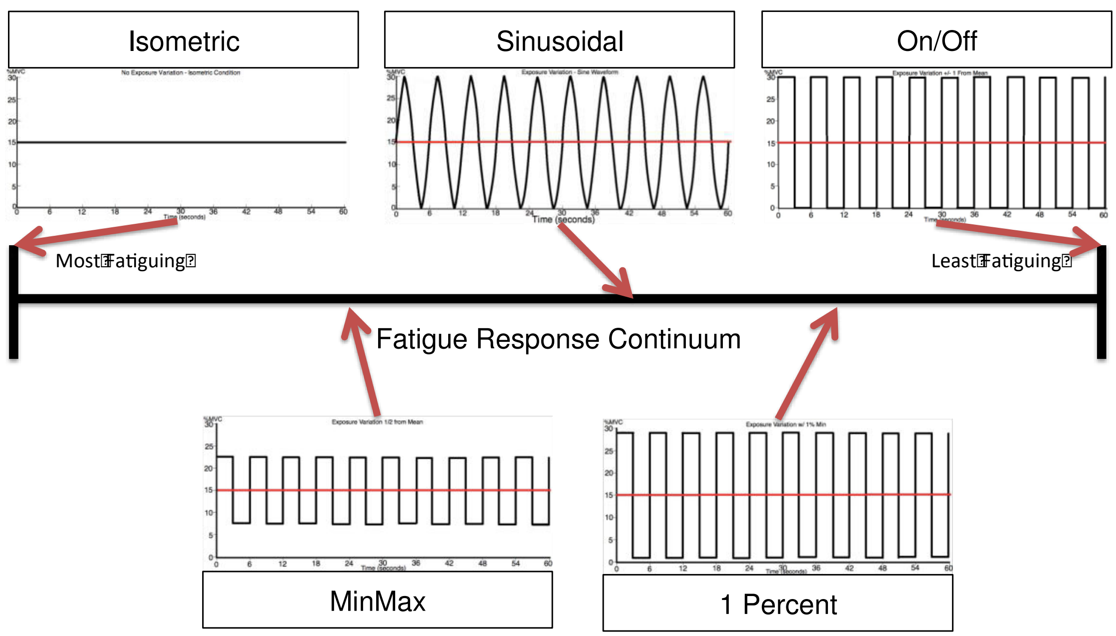

Figure 1.2. Force generation patterns ranging between isometric to intermittent on/off, ranging between the most fatiguing (isometric) to the least fatiguing (on/off) based on various metrics including EMG, force production and physiological measures (Yung et al.,2012).

Their study illustrated mechanical variation as a method of modifying the level of fatigue within a work cycle, even when the average effort is the same for each task. This proof-in-principle approach of Yung and Wells (2012) illustrates that mean force levels, over the course of a task, do not accurately reflect the level of fatigue that may be occurring. It is clear that the variation of mechanical force, throughout a muscle demand time-history, plays an important role in fatigue accumulation. However, it is unknown how fatigue accumulates over the course of a time-history, particularly with respect to efforts that had preceded the force of interest.

Studies examining the relationship between muscle fatigue and complex force patterns provide useful data for the development of new fatigue assessment methods or models, but the relationship needs to be evaluated closely to determine the most important factors that contribute to fatigue onset, fatigue accumulation, and recovery. Aside from the work of Yung and Wells (2012), there is no research to show how fatigue accumulates when tasks are not simple isotonic, or consist of a series of efforts of the same intensity, separated by rest periods of 0% MVC. To understand how fatigue accumulates in the workplace, the research conducted on fatigue must be more closely representative of the type of demands that are performed. Further research must be conducted to improve and develop fatigue evaluation tools that can integrate complex time history data.

1.1.5 FATIGUE MODELLING

Digital human models (DHMs) in ergonomics have allowed ergonomists to predict what forces are required during jobs, long before these tasks are sent to the assembly line (Chaffin, 2001). However, as identified by Brouillette et al., (2012) and Ma et al., (2008), there has been limited advancement into fatigue modelling, particularly in the context of injury prevention in the workplace through digital human models.

Xia and Frey Law (2008) developed a simple physiology-based model for predicting muscular fatigue, consisting of only three compartments representing motor units which are either: 1) fully activated, 2) at rest or 3) completely fatigued (Figure 1.3). In their model, the constant "*F*" represents the rate in which motor units will fatigue, and the constant "*R*" represents the rate at which they will recover. The variable C(t) represents the rate of transfer between resting and active motor units and is influenced by the target load that needs to be achieved.

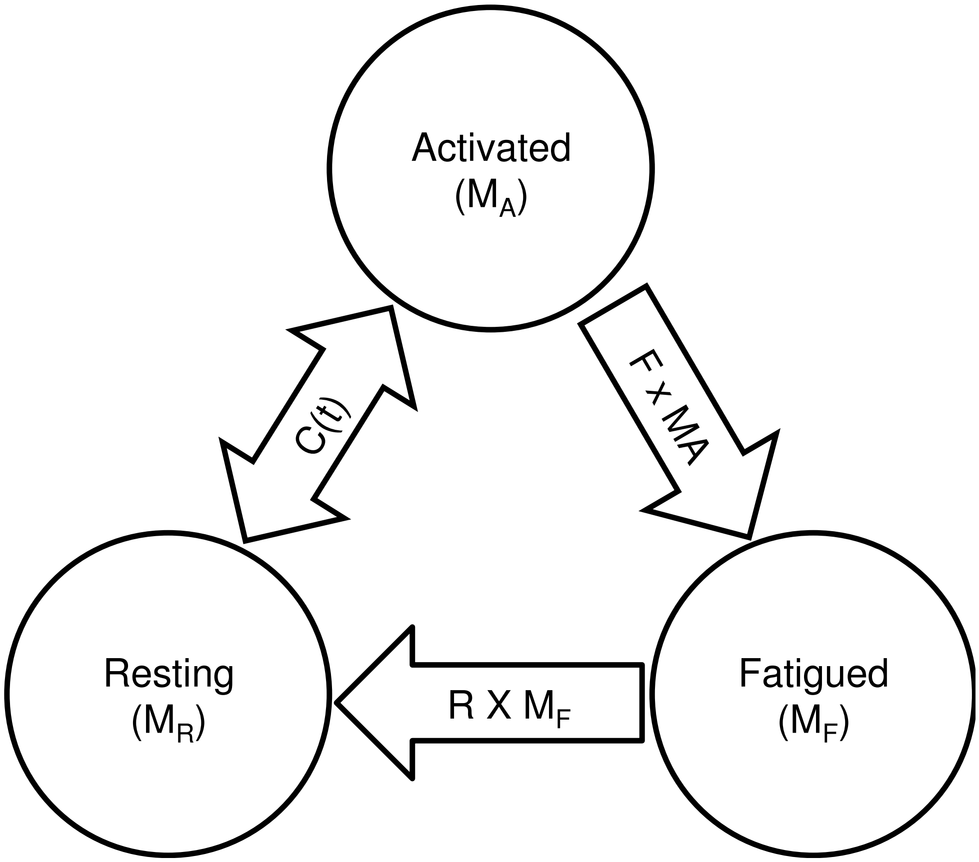

Figure 1.3. Three-compartment model (3CM) of theoretical muscle fatigue (Xia & Frey Law, 2008). Compartments represent motor units that are resting (M_R), fatigued (M_F) and activated (M_A), as well as the rates in which they fatigue, recover, and move from rested to active (*F, R & C(t)*). The flow moves from rested motor units, to active motor units, to fatigued motor units and then back to rested motor units as they recover. To date, the model has only been validated against endurance time predictions from other research of prolonged, isotonic contractions.

Xia and Frey Law (2008) proposed a an advanced muscle recruitment hierarchy, where the flow of motor unit recruitment transfers between slow twitch, intermediate (fast-fatiguable), and fast twitch motor units based on the level of activation of the system. These units had different *F* and *R* coefficients which represented the increased fatigability of units as they progressed from slow to fast. However, the *F* and *R* constants must be defined prior to running through the model, thus these *F* and *R* constants are not dynamic and do not change as the demands change from requiring slow twitch units to fast twitch units.

1.1.6 VALIDATION OF THE THREE-COMPARTMENT MODEL

Frey Law et al., (2012) attempted to validate their model by comparing its outputs against predicted maximum endurance times (MET) from previous research (El ahrache et al., 2006). To modify the output from the model, against the results from the predicted METs, the *F* and *R* coefficients were altered based on the body part where METs were determined. The results from this study showed that METs were predicted accurately (RMS values of between 2.7% for the shoulder and 11.2% for the ankle), however, asymptotes stating infinite endurance emerged between 6.13% MVC for hand or grip, and 9.34 % MVC for the elbow. As stated previously, we know that fatigue can occur with relative efforts less than 5% of MVC for certain tasks (Hagberg, 1981). While *F* and *R* coefficients have been modified to represent these MET curves, further validation is required to examine the ability of the model to accurately model fatigue during more complex tasks.

1.1.7 PURPOSE

The global purpose of this thesis is to evaluate ergonomic tools that assess repetitive work; to enhance our understanding of muscle fatigue during complex force patterns, and to validate and improve on existing methods for determining fatigue accumulation. The end goal of this research is to improve on fatigue models that can be used in digital human models for proactive ergonomic analyses. The chapter specific purposes are as follows:

Chapter 2: A psychophysical study to determine maximum acceptable efforts for a thumb abduction task

Potvin (2012) developed an equation using psychophysical data to estimate maximum acceptable efforts (MAE) as a function of duty cycle (DC). However, only ~6% of the data featured DCs ≥ 0.50. Given the prevalence of high DC tasks in industry (those requiring postural control and persistent, low level exertions (Zennaro et al., 2003)), it is important to validate the MAE equation for DCs above 50%. Thus, the purpose of this study was to determine MAEs for DCs of 0.50, 0.70 and 0.90, and to compare these values to those predicted by the MAE equation.

Chapter 3: Force time-history affects fatigue accumulation during repetitive handgrip tasks

Industrial work often consists of cycles of different tasks completed in sequence to produce a product, or further the completion of a product as it moves down an assembly line. The varying force levels between tasks, combined with different work-to-rest ratios, make it difficult to apply traditional fatigue models to these types of jobs. It is unknown how fatigue accumulates when there are tasks of varying intensity levels within a cycle. The purpose of this study was to examine fatigue accumulation in a repetitive handgrip task where force intensities, within a cycle, varied between 0 and 45% of MVC (in increments of 15% MVC).

Chapter 4: Fatigue accumulation and twitch potentiation during complex MVC-relative profiles

This study was a follow up to the findings of Chapter 3. With a complex force profile, the preceding effort had a significant effect on the fatigue accumulation at a given time. One potential mechanism for this effect was that of post-activation potentiation. This phenomenon leads to increased force generating capacity after a series of conditioning efforts (Sale, 2004). The purpose of this study was to examine how the order of force demands impacted muscle fatigue accumulation, and how fatigue was affected by potentiation.

Chapter 5: A modified version of the three-compartment model predicts fatigue in submaximal tasks with complex MVC-relative histories

The three-compartment model of muscle fatigue could be an effective way to determine level of fatigue at any instance during the course of a simulated force-time history. To date, all validation of the 3CM has consisted only of predicting endurance times for sustained contractions, and not the complex intermittent force patterns that are more closely associated with industrial work. The purpose of this study was to increase the biological fidelity of the model by modifying the fatigue and recovery rates, based on the level of activation and fatigue within the system at a given time, and then optimize the model based on the time-history of measured fatigue levels during 9 different experimental conditions.

In summary, the purpose of this thesis is to: 1) further enhance our understanding of muscle fatigue during complex force demand patterns, 2) to validate fatigue models using these results, and 3) to improve existing fatigue models by incorporating knowledge of fatigue processes. This thesis will aim to provide an accurate tool for muscle fatigue prediction that could be used in a digital human model.

CHAPTER 2:
A Psychophysical Study to Determine Maximum Acceptable Efforts for a Thumb Abduction Task with High Duty Cycles

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ABSTRACT

Potvin (2012) developed an equation using psychophysical data to estimate maximum acceptable efforts (MAE) as a function of duty cycle (DC). However, only ~6% of the data featured DCs ≥ 0.50. The purpose of this study was to evaluate the MAE equation in the high DC range. We tested a repetitive thumb adduction task with DCs of 0.50, 0.70 and 0.90, at frequencies of both 2 and 6 per minute (n = 6 conditions). Participants were trained for 2 hours and tested for 1 hour on each condition. The MAE decreased with increasing DC, and MAEs at 2/min were higher than those at 6/min. When these current six means were added to the original psychophysical studies, the RMS difference of the MAE equation decreased from 7.23% to 7.05% MVC. The values from our study are also consistent with those demonstrating physiological evidence of fatigue during both continuous isotonic and high duty cycle tasks.

PRACTITIONER SUMMARY

The Maximum Acceptable Effort (MAE) equation can be used by ergonomists to estimate acceptable forces and torques where both duty cycle (DC) is known and maximum strength data are available. Our psychophysical study provides evidence to validate the MAE equation for high DC tasks (DC ≥ 0.50). In fact, the relationship between the equation and existing data is improved with the inclusion of our data.

2.1.0 INTRODUCTION

Psychophysical research has made a significant contribution to the determination of acceptable loads for occupational tasks. Snook & Ciriello (1991) summarized years of psychophysical studies, at Liberty Mutual Insurance Company, in their tables of maximum acceptable loads for lifting, lowering, pushing, pulling and carrying. These data were also integrated into the development of the NIOSH Lifting Equation (Waters, et al., 1993) and the manual materials handling assessment methods of Mital, Nicholson, & Ayoub, (1993). Psychophysics has also been used to determine maximum acceptable forces and torques at the hands, wrist and forearm (Andrews et al., 2008; Ciriello, Webster, & Dempsey, 2002; Moore & Wells, 2005; Potvin, Calder, Cort, Agnew, & Stephens, 2006; Snook, et al., 1995, 1997, 1999). Recently, Potvin (2012) performed a meta-analysis on psychophysically determined acceptable forces and torques for upper extremity tasks. He found that acceptable loads decreased exponentially as duty cycle (DC) increased, and this was best represented by the equation:

$$MAE = 1-[DC - \frac{1}{28{,}800}]^{0.24} \qquad [1]$$

In this equation, MAE is maximum acceptable effort, as a percentage a single effort maximum strength, 28,800 is the number of seconds in an 8-hour work day and DC is the ratio of the total effort duration(s) during a cycle divided by the total cycle duration. When specific psychophysical data does not exist for a task, the MAE equation can assist ergonomists in determining if a repetitive task is acceptable based on maximum strength and the normalized maximum efforts required during the cycle.

2.1.1 PSYCHOPHYSICAL RESEARCH FOR TASKS WITH DC ≥ 0.5

One potential issue with the application of the MAE equation is that, of the 69 conditions used in its development, only 12 (17%) had duty cycles of ≥ 0.50 (Ciriello et al., 2002; Moore & Wells, 2005), and only 4 (~6%) of those were > 0.50 (ie. DC = 0.83, Moore & Wells; 2005). Moore & Wells (2005) studied acceptable wrist extensor torques during an in-line screw running task, with various combinations of frequency and effort duration (n = number of tested conditions), resulting in DCs of 0.25 (n = 3), 0.50 (n = 4) and 0.83 (n = 4). They studied 8 females with industrial experience and each worked for 14 days over the course of 4 weeks. Of this, 3 days were used for training and the remaining 11 days were used for psychophysical data collection of one of the combinations of frequency and effort duration. They found that cycle time was not significantly related to the acceptable torques, but that DC was. Potvin (2012) normalized their acceptable torques to MAEs using the maximum torque value of 5.08 Nm from Snook, et al., (1995), because it was not reported in the Moore & Wells

(2005) study. The average MAEs were calculated to be 17.6%, 14.4% and 12.3% MVC for DCs of 0.25, 0.50 and 0.83, respectively.

Ciriello, Webster & Dempsey (2002) determined the maximum acceptable torques of females during six different wrist/forearm torque production tasks, including: 1) supination with a 31-mm and 2) 39-mm screwdriver, 3) supination with a 40-mm yoke, 4) pronation with a 31-mm screwdriver, 5) ulnar deviation with a power grip, and 6) hand grip, at frequencies of 15, 20 and 25 efforts/minute. Participants had 5 days of training, of up to 7 hours per day. To determine the duration of effort, Potvin (2012) used Snook et al. (1997), for similar tasks, to estimate that the four pronation/supination tasks were 1.2 s in duration, and ulnar deviations took 1.08 s. It was not possible to determine durations for the handgrip task, so it was not included in the development of the MAE equation. With the effort durations of the remaining tasks, Ciriello Webster & Dempsey (2002) studied DCs of 0.30, 0.40 and 0.50. Of particular interest for the current study, they found that the DC = 0.50 conditions resulted in average MAEs of 13.8% (pronation; 31 mm handle), 14.2% (pronation; 40 mm handle), 22.9% (pronation; 39 mm yoke), 15.9% (supination; 31 mm handle), for a pooled average of 16.7% MVC. When these data are pooled with the four conditions in Moore & Wells (2005), the average MAE at DC = 0.50 is 15.6% MVC, which is very close to the value of 15.3% predicted with the MAE equation.

2.1.2 RESEARCH SUPPORTING THE MAE EQUATION IN DC ≥ 0.5

Potvin (2012) compared his MAE equation to values obtained from studies providing quantitative physiological evidence of fatigue resulting from high duty cycle tasks (Björkstén & Jonsson, 1977; Byström & Fransson-Hall, 1994; Byström & Kilbom, 1990; Jorgensen, Fallentin, Krogh-lund, & Jensen, 1988; Sjøgaard, Kiens, Jørgensen, & Saltin, 1986) to supplement the limited psychophysical data in the high duty cycle range (DC > 0.5). Compared to the most conservative of the physiological data from Byström & Fransson-Hall (1994), for DCs of 0.50, 0.67 and 0.70, the MAE equation predicted acceptable efforts that were approximately 44% lower (Potvin, 2012). However, lower values would be expected as the MAE equation predicts acceptable efforts for 8 hours, while Byström & Fransson-Hall (1994) demonstrated physiological evidence of fatigue after one hour. Ultimately, the MAE equation was developed predominantly with psychophysical data at DCs only up to of 0.50. Thus, additional psychophysical data are needed from higher DC tasks to validate predicted MAE values in this range.

There are many advantages to using psychophysics in ergonomics. It allows researchers to test industrially relevant tasks with limited instrumentation, and participants establish acceptable forces and torques based on an integration of both biomechanical and physiological feedback (Fernandez & Marley, 2014; Fischer, Brenneman, Wells, & Dickerson, 2012). Given the prevalence of high DC tasks in industry (those requiring postural control and persistent, low level exertions (Zennaro et al., 2003)), it is important to validate the MAE equation for DCs above 50%. Thus, the purpose of our study was to determine maximum acceptable efforts (MAEs) for duty cycles of 0.50, 0.70 and 0.90, and to compare these values to those predicted by the MAE equation.

2.2.0 METHODS

2.2.1 PARTICIPANTS

We studied 15 female participants from the University's undergraduate and graduate student population (age = 23.6 ± 2.9 years, body mass = 63.9 ± 7.2 kg, height = 162.8 ± 11.33 cm). All participants were free from musculoskeletal disorders during the past year and were right hand dominant. We used female participants for this study because most companies design their task to be acceptable to 75% of females, based on the findings of Snook (1978). Each was assigned a subject code, signed a letter of consent and data were protected on a secure hard drive. The University's Research Ethics Board approved participant recruitment methods and study design.

2.2.2 INSTRUMENTATION AND DATA ACQUISITION

A training and testing device was built to place participant's wrist in a slightly extended posture, with the thumb fully abducted and fingers resting on a padded steel bar (Figure 2.1). We used this task, as it represents a novel but simple task for the participants to perform. As our participants were of a university age, it was possible that some had industrial experience. Using this novel task removed any chances of previous experience affecting results. The device could be adjusted to allow all participants to have the same posture. The pad of the thumb interfaced with a thermoplastic covered bolt attached to an s-type load cell (100lb max, Omegadyne Inc., Laval, QC, Canada). A padded adjustable forearm rest supported the forearm during the experiment. A custom-made office chair featured an articulating armrest allowing the participant's to maintain 90 degrees of elbow flexion. Participants sat upright with the chair adjusted comfortably for them. We created four identical testing stations to allow for simultaneous training and/or testing of four participants. Participants watched a video indicating when they were to push, and when they were to rest during the six different duty cycle and frequency combinations. Force data were sampled at 1000 Hz.

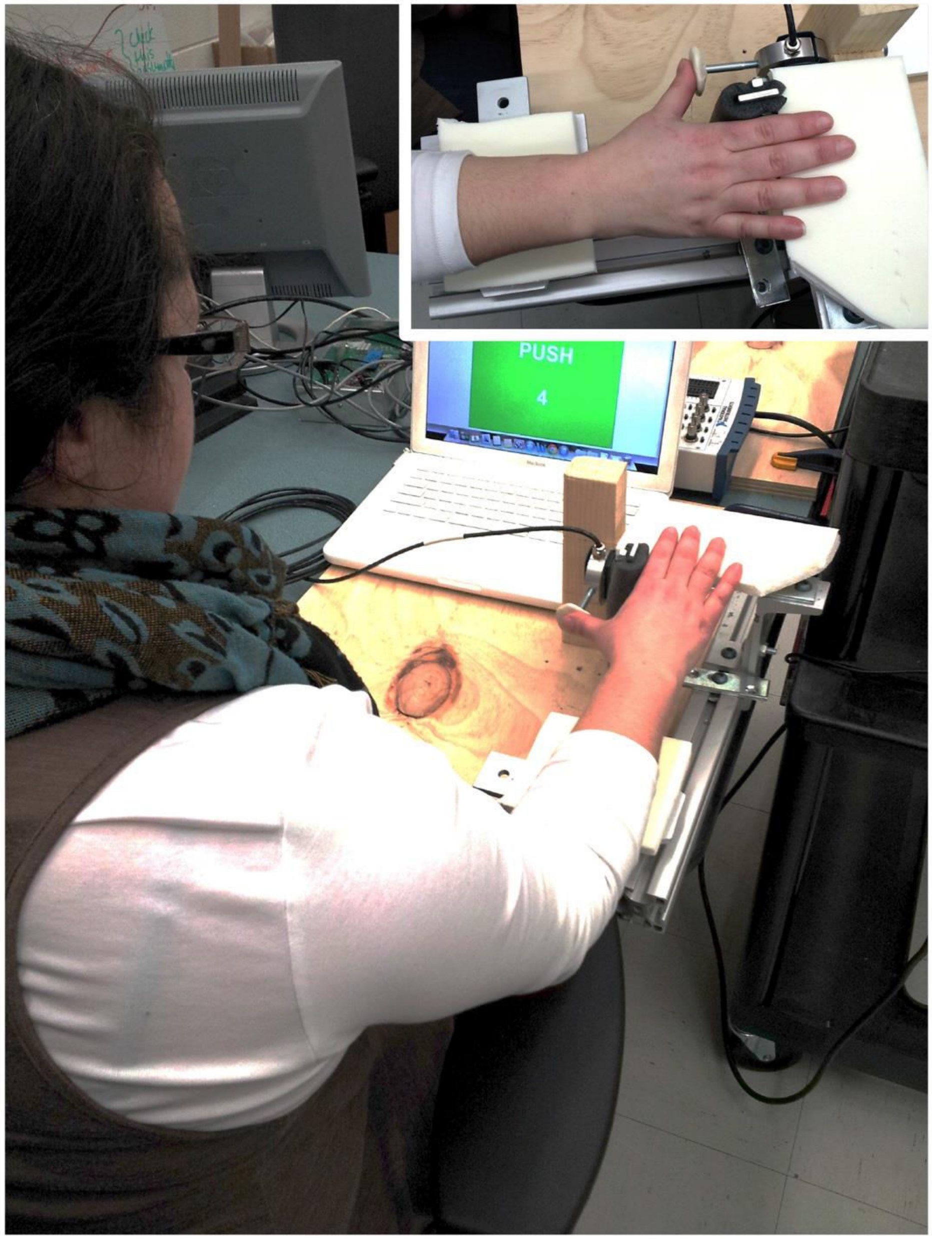

Figure 2.1. Participants were comfortably seated at the testing station with their arm supported by a chair armrest and an adjustable foam forearm pad. The fingers were placed on a padded steel platform, causing the wrist to be slightly extended. The thumb was fully abducted and interfaced with a thermoplastic covered bolt attached to a load cell (Inset of Figure). A computer screen displayed video indicating when participants were to push with their thumb or rest.

2.2.3 EXPERIMENTAL PROCEDURES AND PROTOCOL

We tested duty cycles of 0.50, 0.70 and 0.90, at frequencies of 2 and 6 per minute, for a total of 6 testing conditions with efforts ranging between 5 seconds and 27 seconds in duration (Table 2.1). Though Moore & Wells (2005) found there was no effect of frequency when controlling for DC, we wanted to see if these results carried over to the different cycle times we were testing in this study. Participants were trained for 2 hours on each condition, and trained on only 1 condition per day. The conditions were presented in a random order that was balanced across participants. At least 24 hours elapsed between training sessions so participants could receive sufficient feedback regarding delayed fatigue, soreness or discomfort.

Table 2.1. Effort duration (seconds) for the duty cycles (0.5, 0.7 and 0.9) and frequency combinations (2 and 6 per minute) tested in this study. There were a total of 6 duty cycle and frequency combinations tested.

	Duty Cycle		
Frequency	0.50	0.70	0.90
2/min	15	21	27
6/min	5	7	9

2.2.3.1 Training Sessions

During each training condition, participants determined maximum acceptable force levels in the following manner. They first exerted maximally against the strain gauge three times. The average of these forces was used as the MVC for all subsequent normalizations to MAE. The average MVC was used, as opposed to the true maximum MVC, to present more conservative values. Then, they were instructed to work as if they were paid on an incentive basis, but to exert as hard as possible while still avoiding the development of any discomfort or fatigue in the hand, wrist or forearm at any time during the session. Once the instructions were read, the participants performed the trials while watching a computer screen indicating when they were to push or rest for the condition. After every 15-minute segment, the participants performed an MVC and we compared this value to the pre-trial MVC. We also asked participants to record their level of discomfort on a visual analog scale. If the MVC was less than 90% of the pre-trial MVC, or the discomfort increased during the 2-hour training period, we interpreted this as a sign of fatigue and over exertion and we repeated the instructions. Finally, we asked participants to record their perceived effort level (out of 100%) during each 15-minute segment. If we had observed a sign of fatigue in the previous 15 minute session, and the participants continued to exert at what they felt was the same effort level, we would reiterate the instructions, specifically those instructions about their chosen effort level not causing muscle fatigue. This was repeated for a period of two hours (Figure 2.2).

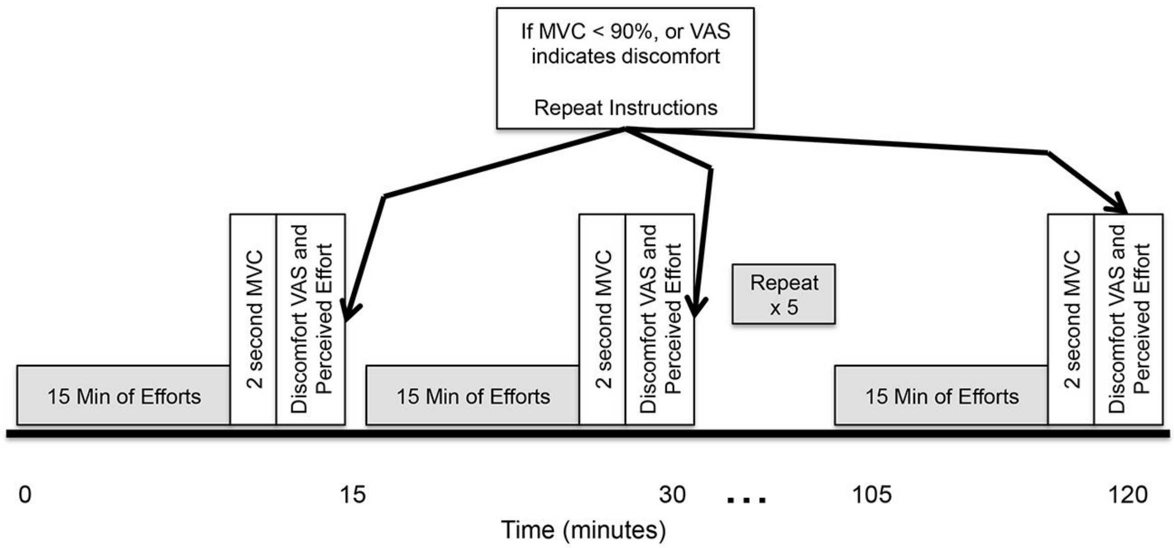

Figure 2.2. Participants performed 15-minute blocks of maximum acceptable efforts that would not cause them fatigue or discomfort if performed over the course of an 8-hour workday. After each 15-minute block, an MVC was performed and was compared to a pre-experiment maximum force level. If the MVC force dropped to 90%, or an increase in discomfort on the visual analogue scale occurred, we repeated the instructions to the participants. For each training session, the effort cycle was repeated 8 times.

2.2.3.2 Testing Sessions

For each of the six conditions, a separate testing day was used. Within each testing session, participants completed four 15-minute segments of self-selected maximum acceptable forces for the given duty cycle and frequency. We asked participants to complete an MVC, visual analog scale, and self-reported effort level at the end of each 15-minute segment, then provided them with feedback on their MVC performance and fatigue level. We recorded all force data, during the final 15-minute segment, for processing and analysis.

2.2.4 DATA ANALYSIS

We processed the final 12 minutes of the last block of maximum acceptable efforts (48 to 60 minutes) to allow the participants to converge on the acceptable effort (Figure 2.3). The force from each of those efforts was first smoothed with a half-second moving average. We then used the middle 80% of each effort to remove any high forces from the impact of the thumb on the interface. We discarded an effort if a participant did not respond to the visual prompt, indicating when to start their push or their rest. We ultimately used 3,468, out of a total of 4,032 efforts (86%). For each of these remaining efforts from 48 to 60 minutes we calculated the mean, and within-effort standard deviation and coefficient of variation during the middle 80% of the effort. For each condition and participant, we then calculated the within-subject average maximum acceptable force and standard deviation and coefficient of variation across the means in the 12-minute window. Each of these average maximum acceptable force values was then normalized to that participant's MVC to calculate the six maximum acceptable efforts for each participant.

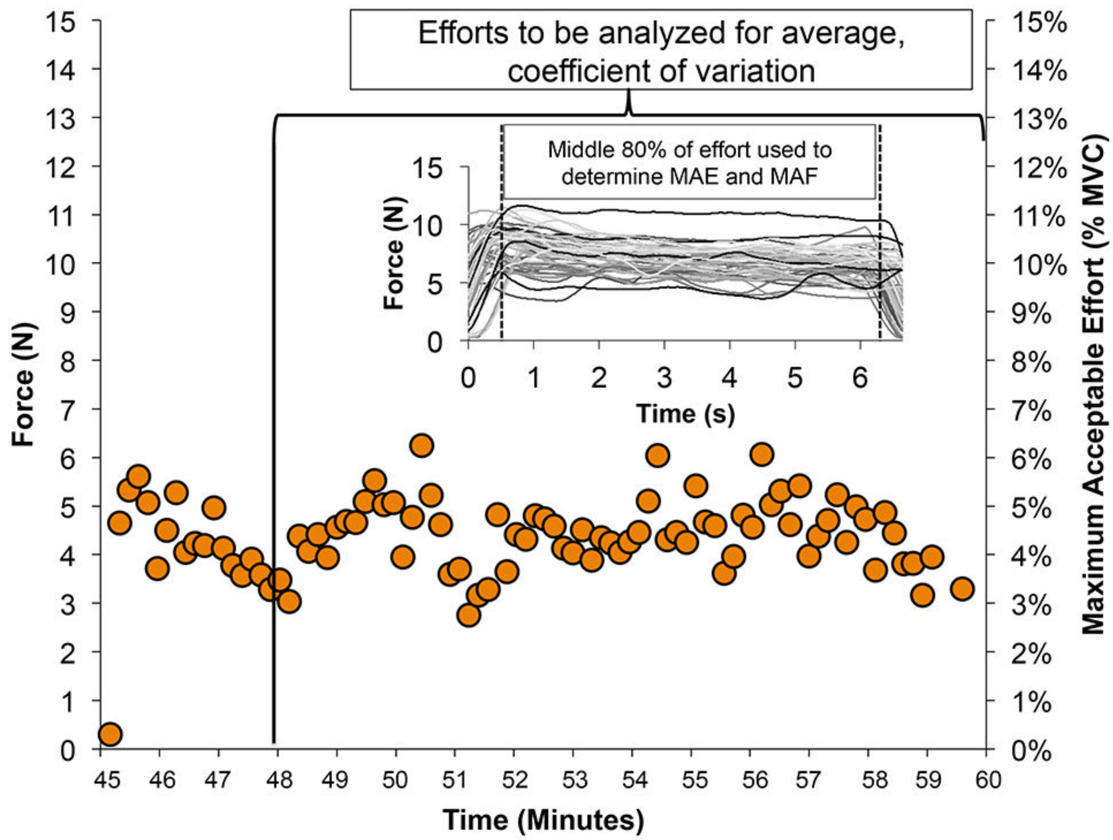

Figure 2.3. We recorded during the last 15-minute segment of each testing condition, and then further analyzed the data from last 12 minutes. This figure is an example of one participant's exertion history for the condition with 7-second efforts and a frequency of 6/min (DC = 0.70). The efforts are plotted as % of MAE (right axis) as well as MAF (left axis). The inset figure shows an example of the force-time histories used to calculate the average, standard deviation and coefficient of variation for each of the efforts during the last 12 minutes of each testing session.

2.2.5 STATISTICAL ANALYSIS

We used 3 x 2 repeated measures analyses of variance (ANOVA) to determine the effects of duty cycle (0.50, 0.70 and 0.90) and frequency (2 and 6/min) on maximum acceptable effort. Tukey's HSD Post-hoc testing was used to determine significant differences from main and interaction effects on the pairwise comparisons between levels of the independent variables. We also compared the results from our study to the predicted results from the MAE equation, for the three duty cycles tested, using a root-mean squared (RMS) difference.

For each of the six conditions, the average within-effort coefficients of variations (CV) were averaged across the participants to provide an index of the consistency of the isotonic efforts. The within-effort CV was calculated, as many of our efforts were greater than 10 seconds long, and we wanted to ensure that the participants were maintaining a steady force level with each effort duration.

2.3.0 RESULTS

One participant performed the task with MAE values of less than 1% MVC for all conditions, often reported discomfort and was observed to have strength decreases following the 15 minute training blocks, likely indicating insufficient motivation. Thus, we removed this participant from the analysis, leaving efforts from 14 participants for statistical analyses.

2.3.1 MAXIMUM ACCEPTABLE EFFORT

The maximum voluntary force (MVF) was 68.9 ± 22.4 N. Each participant's MVF was used to normalize MAE values as a percentage of MVF.

There was a significant main effect of duty cycle ($p<0.001$) on MAEs, with values at DC = 0.50 (8.48 ± 5.95% MVC) being significantly higher than those at DC = 0.70 (6.61 ± 5.04% MVC) and DC = 0.90 (5.75 ± 4.01% MVC). While the MAE values, at DC = 0.7, were slightly higher than those at DC = 0.9, they were not statistically different. The MAEs at DC = 0.70 DC and 0.90 DC were 22% and 32% lower than DC = 0.50, respectively. There was a significant main effect of frequency ($p<0.05$), with MAE values being higher at a frequency of 2/min (7.46 ± 5.75% MVC) than at 6/min (6.43 ± 4.65% MVC) (Table 2.2). There was no interaction between DC and frequency.

The average within-effort MAE CVs was 14.6% across the six combinations of duty cycle and frequency (Table 2.3). This demonstrates that participants maintained relatively constant forces during each effort, even for the longer durations (up to 27 s). The average between-subject CVs of MAE values was 71.2%, indicating a high inter-participant variability between the DC and frequency combinations.

Table 2.2. Maximum acceptable efforts (MAE), as a percentage of maximum strength (MVC), determined psychophysically during the thumb adduction task. Duty cycles of 0.50, 0.70 and 0.90 were studied at frequencies of 2 and 6 per minute. Mean (standard deviation) values are presented for each condition.

	Duty Cycle			
Frequency	**0.50**	**0.70**	**0.90**	**Mean**
2/min	9.46	6.66	6.26	7.46
	(7.39)	(4.23)	(4.33)	(5.75)
6/min	7.49	6.56	5.23	6.43
	(4.10)	(5.89)	(3.74)	(4.65)
Mean	8.48	6.61	5.75	
	(5.95)	(5.04)	(4.01)	

Table 2.3. The average within-effort coefficients of variation of the thumb abduction forces for each of the six conditions tested.

	Duty Cycle			
Frequency	**0.50**	**0.70**	**0.90**	**Mean**
2/min	13.9%	18.1%	14.1%	15.4%
6/min	14.0%	15.0%	13.7%	14.2%
Mean	13.9%	16.6%	13.9%	14.8%

2.3.2 COMPARISON TO MAE EQUATION

The RMS difference, between the maximum acceptable efforts found in the current study (Table 2.2), and the values predicted with the MAE equation, was 4.52% MVC (n = 6). This was actually lower than his RMS difference of 7.23% MVC across the 69 conditions used to develop the equation (Potvin, 2012). When including the data from the current study, the overall RMS difference decreased to 7.05% MVC (n = 75).

In the development of the MAE equation, the best exponent to fit with psychophysical data was 0.24. However, as noted, 57 of the 69 (83%) conditions used to develop the equation had DC < 0.50. The most appropriate exponent was determined again, using only data from DC ≥ 0.50 (n = 18), including our 6 conditions, the 4 conditions from Ciriello, Webster & Dempsey (2002) and the 8 from Moore & Wells (2005). It is interesting to note that the exponent with the lowest RMS difference (5.03 % MAE) remained at 0.24, even when only based on data with DC ≥ 0.50.

2.4.0 DISCUSSION

The main finding of this study is that maximum acceptable efforts (MAE) decreased slightly, but significantly, with increasing duty cycle. The finding of decreased MAE with increasing DC is in agreement with the Moore & Wells (2005) and support the predictions from the MAE equation at higher duty cycles (Potvin, 2012). Prior to the current study, the MAE equation predictions, for DC > 0.50, were based on only one psychophysical study with four conditions.

The values predicted by the MAE equation are significantly lower than those shown to demonstrate physiological signs of muscle fatigue after 1 hour of exercise (Figure 4 from Potvin, 2012). The psychophysical studies used to develop the MAE equation determined MAEs that would avoid fatigue over an 8-hour workday, so they would be expected to be substantially lower than efforts proven to result in physiological evidence of fatigue after one hour. The data from the current study is consistent with the previous psychophysical studies, as they are well below the lower bound of physiological data used to support the creation of the MAE equation.

Physiology studies of muscle fatigue were previously used to support the MAE equation's predicted values for conditions where the duty cycle was higher than 0.5 (Potvin, 2012). Efforts of 43.7%, 27.8%, and 21.3% MVC were shown to result in physiological evidence of fatigue after one hour at duty cycles of 0.3, 0.5, 0.7 (Björkstén & Jonsson, 1977). More importantly, a 5% MVC effort resulted in fatigue after only one hour of sustained contraction (DC = 1.00) (Jorgensen et al., 1988; Sjøgaard et al., 1986). Our current MAEs appear to be consistent with the variability around the predicted curve from Potvin (2012) and appropriately below the conditions resulting in evidence of fatigue after one hour (Figure 2.4). It is possible that the values at DC = 0.50 were somewhat under estimated by the participants, and those at DC = 0.90 were somewhat over estimated. However, we are confident that the DC = 0.70 MAEs (6.7% and 6.6% MVC) represent a good estimate of what is acceptable at that duty cycle, and these are even somewhat lower than is predicted with the MAE equation (8.2% MVC).

Steven's power law is used to explain the relationship between perceived sensation magnitude and physical stimulus intensity (Stevens, 1957). This relationship varies significantly across stimuli, but can be explained by equation 2:

$$\Psi = kS^n \qquad [2]$$

Where Ψ= the sensation magnitude, S= the stimulus intensity, and k = a proportionality constant based on the units. The relationship is represented by the exponent, *n*. This relationship is represented by exponents of between 1.7 and 2.0 for force production (Cafarelli, Cain, & Stevens, 1977; Stevens & Mack, 1959; Stevens, 1957). If an exponent of 1.85 (the average between exponents of 1.7 and 2.0) is used to represent the relationship between physical stimuli and sensation, an increase of 0 to 10% MVC would only represent a perceived effort change of 1.4% (or 14% of the physical stimulus change). Moving from 10 to 20% of MVC would only represent a 3.7% change in perceived effort, or 37% of the actual physical change in effort. Applying this to the MAE equation, the decrease in physically acceptable effort between a DC of 0.7 and 0.9 is 5.1 % MVC (8.2%

MVC to 2.5% MVC; Figure 2.5). With an exponent of 1.85, this would result in a perceived decrease of only 0.9% in the sensation (only 15% of the actual stimulus decrease). This highly non-linear relationship between perception and force production may be the reason for the lack of statistically different changes in our MAEs between DCs of 0.7 and 0.9, where the force levels were very low.

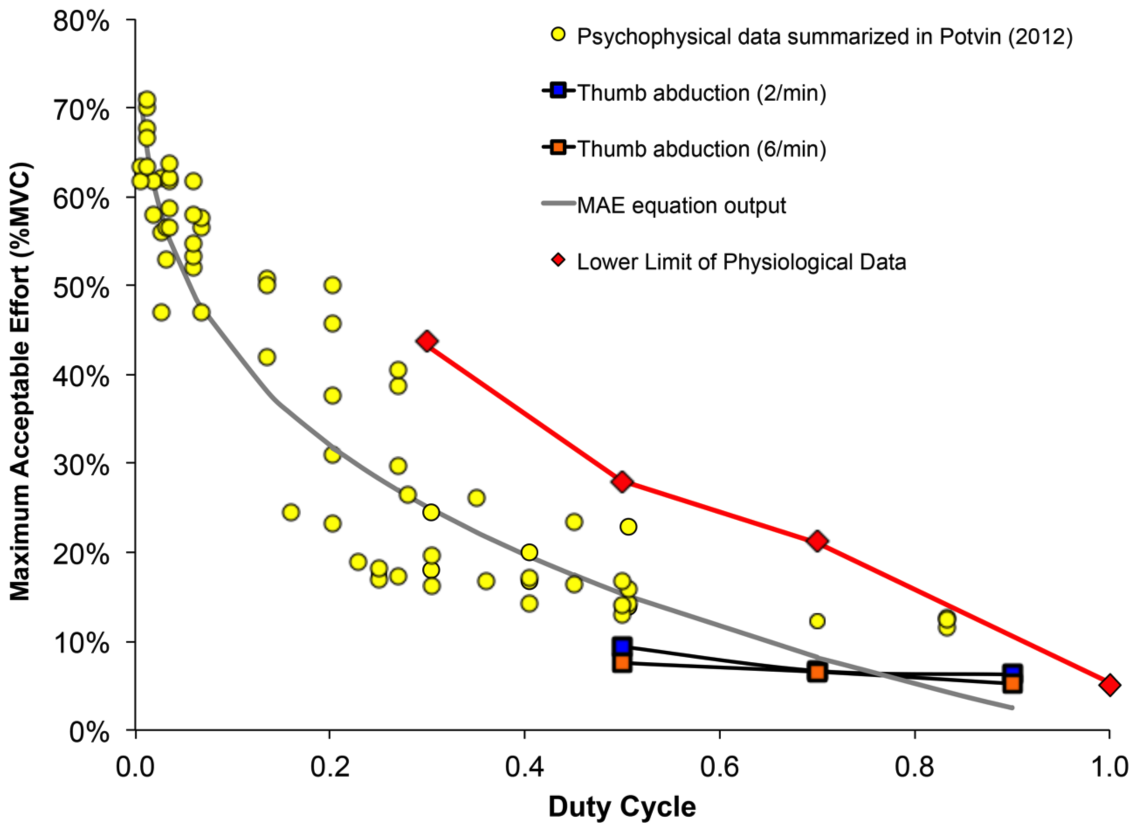

Figure 2.4. Maximum acceptable efforts from the psychophysical data summarized in Potvin (2012) (n = 69) are shown with the data from the current study, with thumb adduction. Additionally, we present the lower limit of physiological data Potvin (2012), used to support the high duty cycle range of the equation. Adding our higher duty cycle conditions of 0.50, 0.70 and 0.90 reduced the RMS difference, between the empirical data and the equation outputs, from 7.23% MVC (n = 69) to 7.05% MVC (n = 75). The exponent of 0.24 still provided the best fit when only considering conditions with DC ≥ 0.50 (n = 18).

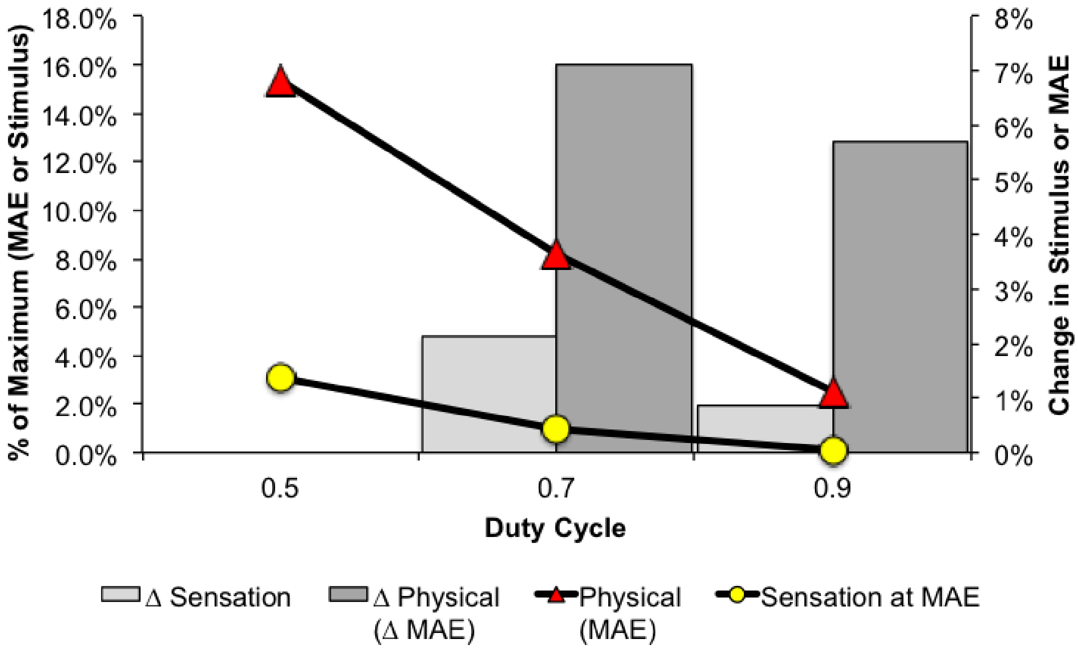

Figure 2.5. Between a DC of 0.7 and 0.9, the physical stimuli (% MAE) changes by 5.1 % MVC (dark grey bar in the figure above). Using an exponent of 1.85 in the Steven's Power Law equation, the change in stimuli between these two points would only be 0.9 % (light grey bars in the figure). There is a much greater drop in the % MAE between the DC of 0.5 and 0.9 than drop in the perceived stimuli, which may be why participants over estimated their MAE during the highest DC.

Moore & Wells (2005) found that, when accounting for duty cycle, frequency was not a significant predictor of acceptable effort; at least for the conditions they tested. Conversely, in the current study, there was a main effect of both frequency and duty cycle. While this was statistically significant, the 13.8% relative decrease in MAEs from frequencies of 2/min to 6/min represented only an absolute decrease of 1.03% MVC. This effect should be further explored in future studies, to see if it applies to other frequencies and DC combinations.

Moore (2000) examined high duty cycle tasks and evaluated the applied duty cycle (the time of the task where force generation was required) versus the biomechanical duty cycle (the time spent with muscle active and force being applied). They found that the biomechanical duty cycle was longer than the time that was spent applying the task force. This effect was more prominent in tasks with shorter cycle times compared to those with longer cycle times. For example, with the applied DC = 0.83, the biomechanical DC was shown to be closer to 0.90. As a result, the 6/min frequency in our study may actually lead to longer muscle duty cycles, leading to lower MAEs reported by the participants. The MAEs reported in Moore (2000) are approximately 12.3%, which are higher than those predicted by the MAE equation (4.3%).

Rohmert, (1973) assumed that there is no reduction in maximum strength during work if holding forces are limited to 15% of maximum strength (or less). As summarized by Potvin (2012), efforts of this intensity have repeatedly been shown to be unacceptable for repetitive and static tasks. Jonsson, (1988) proposed that muscles should remain below an effort intensity of 10% MVC for at least 50% of an 8 hour day (DC = 0.50), and below 2% MVC for at least 90% of an 8 hour day (DC = 0.90). Our MAEs at DC = 0.50 are very similar to the permissible levels established by Jonsson (1988), but are higher at DC = 0.90. While the current study's values are lower than the predicted MAE values, they appear within the range of physiologically tolerable forces that will not contribute to muscle fatigue at a duty cycle of 0.5, though they are higher at a duty cycle of 0.9.

One limitation, of using psychophysics to determine acceptable effort levels is the tendency to incorrectly predict values during highly repetitive tasks. Karwowski & Yates (1986) stated that psychophysics should not be used to determine standards, for lifting tasks with frequencies greater than 6/min as values were being over predicted. Kim (1990) also determined that psychophysics should not be used as the deciding factor when performing ergonomic analyses of more repetitive tasks, as acceptable work loads determined with this method exceed limits set by physiological criteria. Potvin, (2014) summarized data from biomechanical, physiological, and psychophysical studies to determine acceptable lifting limits. The limiting criteria for acceptable loads was the biomechanical criterion between frequencies of 0.002 and 0.033/min, the psychophysical criterion between frequencies of 0.2 and 4.3/min, and physiological criterion between frequencies of 4.3/min to 12/min. Psychophysical criterion were found to significantly over predict acceptable lifting loads during these high frequencies (Fernandez & Marley, 2014; Potvin, 2014). The physiological demands associated with a complex, whole body task (such as lifting) would be significantly different (and far greater) than those seen in the simple thumb adduction task we tested in our study. It appears that subjects may have over predicted their MAEs at the higher frequencies and/or duty cycles and this may explain the higher than expected MAEs at DC = 0.90, though the mechanism for this difference may be different than the one observed previously for lifting.

Psychophysically determined MAEs rely on a participant's ability to integrate sensory feedback and determine the level of efforts that would cause them unacceptable discomfort or fatigue over the course of an 8-hour day. If participants do not receive adequate training, or testing sessions do not occur with enough time between one another, to allow for the differentiation of testing conditions, it is possible that results could be adversely affected (Ciriello, Snook, Webster, & Dempsey, 2001; Wu & Chen, 2003). Potvin (2012) only included psychophysical studies, in the development of his MAE equation, if the participants: 1) determined MAEs for 8 hour days, 2) were tested on different days, and 3) did not use any assistive devices for the task. Our study controlled for duty cycle and frequency, with participants being asked to determine MAEs for an 8-hour duration. Additionally, our participants did not use any assistive devices, and their training and testing sessions were all conducted on separate days. Finally, our participants performed the thumb adduction task for 45 minutes prior to having their last 15 minutes recorded for processing. These strict criteria were adhered to during the collection of our study, allowing us to be confident in the MAE values we determined from our three duty cycle conditions, created through various combinations of frequency and effort duration.

As previously mentioned, this is one of the only psychophysical studies with duty cycles at ≥0.5. While we strictly adhered to the recommended guidelines for conducting psychophysical research for this type of task, we saw very high variability between our subjects in each of our testing conditions. We assumed that these recommendations would apply for all duty cycles, but given the variability in our data, it is possible that much more training is required than the 2 hours per condition that we performed in order to obtain more consistent MAE values.

2.5.0 CONCLUSION

Our data shows a significant decrease in maximum acceptable effort with increasing duty cycle with duty cycles of 0.5, 0.7, and 0.9. The MAE equation actually has a lower RMS difference between the predicted values and actual psychophysical data when our data is included in the analysis (RMSD of 7.23% (n = 69) and 7.05% (n = 75), respectively). The current data, as well as the predicted values from the MAE equation, lie well beneath physiological data that illustrated signs of fatigue during tasks with high duty cycles during less than 8 hours of work (Figure 2.4).

Where maximum strength data are available for a task, the MAE equation allows ergonomists to scale those strengths to determine maximum acceptable forces based on the duty cycle of a task. This ergonomics tool allows for the assessment of jobs that are highly repetitive with long duty cycles, however, there was a relative lack of psychophysical data to validate the equation for high duty cycles. The data from our study lend support to the validity the MAE equation for tasks up to at least DC = 0.70, although it is not clear if our psychophysical data over estimate MAEs, or the equation under estimates MAEs, for DCs closer to 0.90.

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CHAPTER 3:

Force Time-History Affects Fatigue Accumulation During Repetitive Handgrip Tasks

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ABSTRACT

Muscle fatigue is associated with a higher risk of workplace injury, in particular during repetitive tasks. This study aimed to identify the effect of a complex MVC-relative time history (a task with multiple different submaximal effort levels) on fatigue accumulation and recovery during a handgrip task. We measured surface electromyography of the brachioradialis (BRD) and flexor carpi ulnaris (FCU) of ten right hand dominant females with no history of upper limb injury while they performed a complex submaximal visually targeted gripping task. The task consisted of 15%, 30%, 45%, 30%, and 15% maximum voluntary contraction (MVC) plateaus. Each plateau was held for 15 seconds, followed by a 3 second MVC and 3 seconds of rest. The "pyramid" was repeated until fatigue criteria were met. Grip force, average EMG and mean power frequency (MnPF) for first cycle and fatigued last cycle, were compared. Post-plateau peak grip force was on average 20.5% MVC lower during the last cycle ($p < 0.01$). Post-plateau grip forces decreased on average by 5.1 % MVC after the first 15% MVC plateau (from baseline), by 5.3% MVC after the 30% MVC plateau and 6.8% MVC after the 45% MVC plateau. Further accumulation of fatigue after the second 30% MVC plateau however was minimal, only decreasing by 1.6% MVC. Recovery appeared to occur during the last 15% MVC plateau with an increase in post plateau grip force of 1.6% MVC. Interestingly, MnPF parameters confirmed significant fatigue accumulation during the back end of a force pyramid. We conclude that in a pattern of contractions with ascending, then descending force intensity, voluntary force recovery was present when the preceding force was of a lower intensity. These findings indicate preceding demands play a role in fatigue accumulation during complex tasks.

Keywords: Neuromuscular fatigue, force time history, complex tasks, handgrip

3.1.0 INTRODUCTION

Muscle fatigue is a complex and highly researched topic, with important implications for ergonomics. Fatigue is a process that decreases the contractile capacity of muscles. When this occurs in the workplace, the force producing capacity of the worker is diminished, and tasks require a higher relative effort. Maintaining the same pace and/or force level becomes more difficult, increasing the likelihood of sustaining an injury. In ergonomics, fatigue models are used to determine acceptable rest allowances for a given exertion level and duration. This approach, of determining the maximum holding or endurance time for an exertion and the required rest allowance, was first modelled by (Rohmert, 1973). That model, however, is criticized for predicting that efforts less than 15% maximum voluntary contraction (MVC) can be held indefinitely. Interestingly, in the same communication, data are presented, from Rohmert's work in 1962, showing that a static hold at slightly higher than 15% (ie. 20% MVC) reduced MVC production by 40% after only 6 minutes (although the type of contraction is not described).

Many authors have since shown that fatigue development occurs at intensities much lower than 15% MVC (Björkstén & Jonsson, 1977; Mathiassen & Åhsberg, 1999; Sato et al., 1984). Shoulder flexor fatigue occurs in less than 20 minutes with an 8% MVC static contraction (Mathiassen & Åhsberg, 1999), elbow flexor fatigue occurred within 60 minutes at 7.9% MVC (Björkstén & Jonsson, 1977). As a result, the guidelines proposed by Rohmert (1973) would possibly recommend acceptable work limits that would likely result in fatigue in an occupational setting. It is important that the fatiguing contributions of these low level contractions are accounted for in future models to be used in the workplace.

In 2009, a review of the literature found 24 fatigue models using the maximum endurance time approach, with some being joint specific while others were more general (El ahrache & Imbeau, 2009). used an equation, where the normalized force level was set to an exponent to predict endurance times, to define fatigue. They also included different constants for each joint. Frey Law & Avin, (2010) also developed a joint-specific fatigue model and examined differences in endurance time between joints. With regards to their utility in ergonomics, a limitation of all of these models is that they were developed using endurance tasks, or tasks that featured intermittent isotonic contractions of the same intensity. These types of exertions are not often found during modern industrial work.

Industrial tasks often require varying levels of effort, which affects fatigue accumulation. A study by Byström & Fransson-Hall, (1994) determined the effects of various intermittent handgrip contractions on fatigue accumulation, as measured by lactate concentration. Continuous contractions accumulated lactate concentrations far more quickly than contractions at the same intensity with intermittent rest breaks. However, a limitation of that study was that complete rest occurred during the intermittent contraction condition, which often isn't the case in industrial tasks and, therefore, the results may not be directly applicable to ergonomics.

Recently, Yung et al., (2012) assessed the fatiguing effects of intermittent contractions, with and without complete rest, as assessed by decreases in force generating capacity. They tested 5 elbow extension fatigue conditions, all of which had an average MVC-relative force demand of 15% MVC. One condition was a continuous 15% MVC contraction and four were intermittent in nature, with only one of those having a complete rest phase. Each intermittent task cycled through the same maximum and minimum demand level. They found that, in spite of the each condition having the same average demand, the 5 conditions induced differing levels of fatigue accumulation. The continuous, isotonic condition caused the greatest level of fatigue. The one intermittent condition, with a complete rest phase, resulted in the least amount of fatigue.-Interestingly, the intermittent contractions without complete rest did still allow for substantial fatigue recovery, compared to the isotonic condition.

Based on the fact that most of the available research data is based on either isotonic endurance trials, or simple intermittent tasks, it is still unknown how fatigue accumulates during the course of complex tasks with widely varying force levels, interspersed with rest. On an assembly line, a worker may move from lifting a tool, to tightening a bolt, to installing a weather strip on a door. These tasks all consist of varying MVC-relative force levels, and muscle demands, and will all contribute to the interaction between fatigue and recovery. The purpose of the current study was to further examine fatigue accumulation throughout the course of a task that features a complex force demand time-history.

3.2.0 METHODS

3.2.1 PARTICIPANTS

The study consisted of ten right hand dominant females (23.3 ± 3.7 years, 1.65 ± 0.1 m, with 63.4 ± 7.3 kg) with no history of upper limb injury for this study. Participants provided written informed consent prior to testing. The study received clearance from the University Research Ethics Board.

3.2.2 APPARATUS

Force data were collected using a digital pinch/grip dynamometer with an integrated force multi analyzer (MIE Medical Research Limited, Leeds, UK). Surface EMG were differentially amplified (gain = 1000-5000, input impedance = 10 GΩs, 10-1000 Hz, CMRR = 115 dB at 60 Hz, Bortec, Octopus AMT-8, Calgary, AB, Canada) and A/D converted using a 12-bit card (National Instruments, Austin, TX). We sampled grip force and EMG at 2000 Hz using custom LabVIEW software (National Instruments, Austin, TX.).

3.2.3 PROTOCOL

Participants began the experiment with a familiarization protocol using their non-dominant (left) hand. This process familiarized the participants to the visually targeted gripping task, without eliciting fatigue in the dominant hand. Participants performed two grip MVCs with their left hand using a handgrip dynamometer and the average was used later to normalize the force profile we presented as feedback on the computer screen during the practice trial (Figure 3.1). Participants then stood in front of the computer screen with their arms relaxed by their side while holding the dynamometer in their left hand. We presented the normalized profile on the screen, and they were instructed to, as accurately as possible, trace the profile as real-time grip force feedback appeared on the screen. The practice protocol consisted of 15-second plateaus of 15% MVC, then 30% MVC and then 45% MVC, presented in a random order, followed by a three-second maximum effort and three seconds of rest.

During the training and test session, participants held the handgrip dynamometer directly at their side, with the wrist in a neutral posture. There was a mark on the dynamometer where participants were instructed to put the webbing between their thumb and the index finger while gripping (Figure 3.1). This ensured that the moment arm in the dynamometer was the same throughout all trials. While there was no brace to maintain wrist posture, the aperture of the handgrip dynamometer was adjusted to be consistent with the participants' grip spans. During the practice and experimental session, the participant was told to modify their posture if the wrist angle changed (in either radial/ulnar deviation or flexion/extension).

After participants completed the practice protocol, they were instrumented with surface electrodes over the muscles bellies of the brachioradialis (BRD) and flexor carpi ulnaris (FCU). These muscles were chosen, as they exhibited the greatest signs of muscle activity during a pilot testing session involving 6 muscles in the forearm. We decided to only examine two muscles due to the difficulty of placing 6 sets of electrodes on the limited space of smaller female forearms. We shaved the skin over the electrode sites, if necessary, and scrubbed with rubbing alcohol. The experimenter landmarked electrode locations and then confirmed with manual palpation of contraction and presence of electromyography (EMG) during a reference contraction (as per Perotto & Delagi, (2011)). Participants then performed three MVCs, with 2 minutes rest between contractions to avoid fatigue. We used the average maximum grip force from these trials as the baseline pre-fatigued grip force and also used to normalize the force profile and their real-time feedback during the experimental protocol.

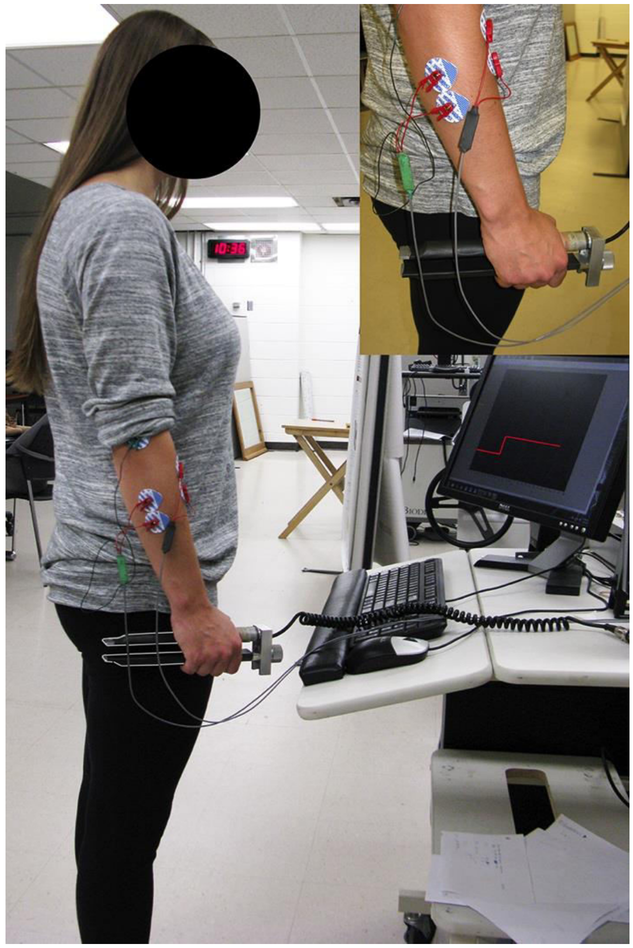

Figure 3.1. Participants held the handgrip dynamometer at their side, with the wrist in a neutral posture. Participants were instructed to trace a template on a computer monitor by squeezing the dynamometer to match a red line with a grey template line. During the trial, the participants were instructed to keep the hand by the side, the arm close to the body, and the webbing of the thumb positioned on the dynamometer at the same place throughout the trial.

The experimental protocol consisted of a pyramid of plateaus, first ramping up with plateaus of 0% MVC then 15% MVC then 30% MVC then 45% MVC, and then ramping back down to 30% MVC and then finally to 15% MVC. Each plateau was held for 15 seconds, followed immediately by a 3 second MVC then 3 seconds of rest, before moving on to the next plateau (Figure 3.2). Participants repeated the entire pyramid cycle until the post-plateau MVC was less than 65% of their pre-fatigued maximum, or when they could not maintain two consecutive submaximal plateaus. After they met the failure criterion, the participants completed the pyramid of that cycle, as well as possible, and the protocol was terminated.

3.2.4 DATA ANALYSIS

Force data were smoothed using a 0.5 second moving average and normalized to pre-trial MVC force. We processed the EMG signal from BRD and FCU using a band pass 6^{th} order Butterworth filter from 20 to 500Hz. During each force plateau, we used the band pass filtered EMG data to calculate mean power frequency (MnPF) once per second. These measurements excluded the first and last 1 second of each plateau. This removed any influence of the start of the plateau contraction, as well as the ramping up to the MVC. The MnPF for the BRD and FCU were then fit to a second order regression equation. We calculated the average MnPF from the initial 1 second at the beginning of the submaximal plateau and for the final 1 second at the end of the submaximal plateau. The filtered EMG signals were then full wave rectified, smoothed with a half second moving average and then normalized to their respective pre-trial MVEs to determine percent activation levels.

3.2.5 STATISTICAL ANALYSIS

For each participant, we analyzed the first and last cycle (defined as the last cycle where all plateaus could be performed). For the maximum grip strength recorded after each plateau, a 2x6 ANOVA was performed with repeated measures. The independent variables were Cycle (first, last) and Plateau (0 %MVC, ascending 15, 30 and 45 %MVC, and descending 30 and 15% MVC). These levels will now be referred to as 0%, A15%, A30%, 45%, D15% and D30%, respectively.

For the average EMG (aEMG) amplitude dependent variables, separate ANOVA's were run for each muscle (BRD & FCU) for the 15% and 30% plateau levels. The 2x2 repeated measures ANOVA's included the factors of Cycle (first, last) and Direction (ascending, descending). There were a total of 4 ANOVAs run on this dependent variable.

For the MnPF dependent variables, four separate ANOVAs were run for each combination of muscle (BRD & FCU) and plateau level (15% and 30%). Each was a 2x2x2 ANOVA with repeated measures, including Cycle (first, last) and Direction (ascending, descending) and Plateau (2s and 14s, into the plateau).

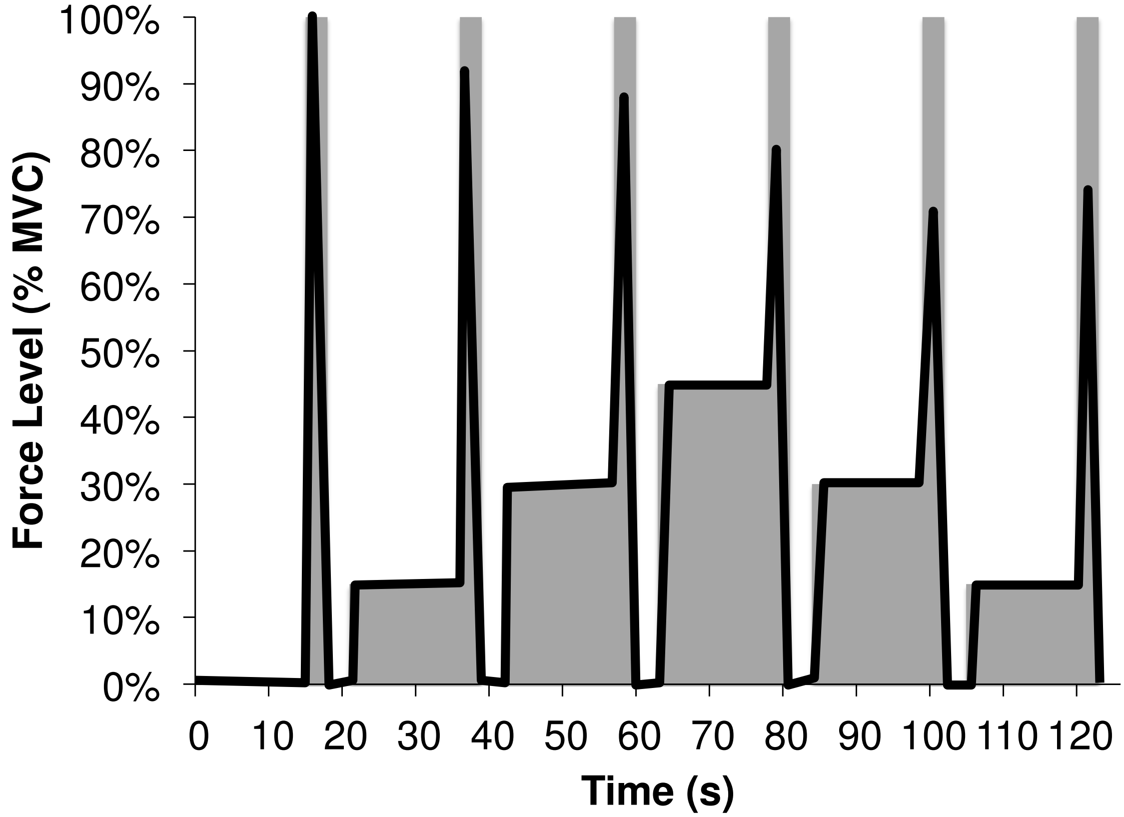

Figure 3.2. The force tracing profile (shaded in grey) performed by participants consisted of 15 second long plateaus, followed by a maximum voluntary contraction (where participants ramped up to their maximum force and came back down to rest within 3 seconds), followed by 3 seconds of rest. The pyramid profile ranged from a rest period (0 % MVC), to 45 % MVC, with plateaus of 15 and 30 % MVC in between. The plateau forces were absolute, but the MVCs would not necessarily get to the pre-fatigued maximum once the trial started (as highlighted by the dark line in the figure, which progressively falls below 100% MVC in the template).

Finally, a paired samples t-test was performed on all dependent variables to evaluate differences between the final cycle as participants performed different numbers of cycles of the experimental protocol. Significance was set at $p<0.05$ for all ANOVAs. All post hoc tests were performed with a Tukey HSD (at either $p<0.05$ or $p<0.01$). All statistical analysis was performed using IBM SPSS Statistics (Version 20, IBM Corporation, New York, USA).

3.3.0 RESULTS

Five participants completed 2 cycles of the task before meeting the fatigue criteria, and five participants completed 3 cycles. A paired t-test confirmed that there was no significant difference between the last cycles of those who completed 2 cycles versus those who completed 3 (p>0.05). The average force in the last cycle for those completing two cycles was 66.84 ± 5.04 % MVC, and 71.67 ± 5.36 % MVC for those who completed three cycles.

3.3.1 MAXIMUM HANDGRIP FORCE

There were significant main effects of Cycle and Plateau (both p<0.0001) on maximum grip strengths recorded at the end of each plateau. Pooled across all Plateaus, the average grip strength decreased 23.1%, from 89.0 ± 11.1% MVC in the first cycle to 68.5 ± 10.6% MVC in the last cycle.

Pooled across Cycles, there was a progressive decrease in grip strength as the Plateaus progressed. The strengths measured after the 0% MVC plateau, were significantly higher than all subsequent plateaus from A30% to D15% (p<0.01). Those at A15% were higher than all subsequent plateaus from 45% to D15% (p<0.01), and those at A30% were higher than all subsequent plateaus from 45% to D15% (p<0.05). There were no differences between 45%, D30% and D15% (Figure 3.3).

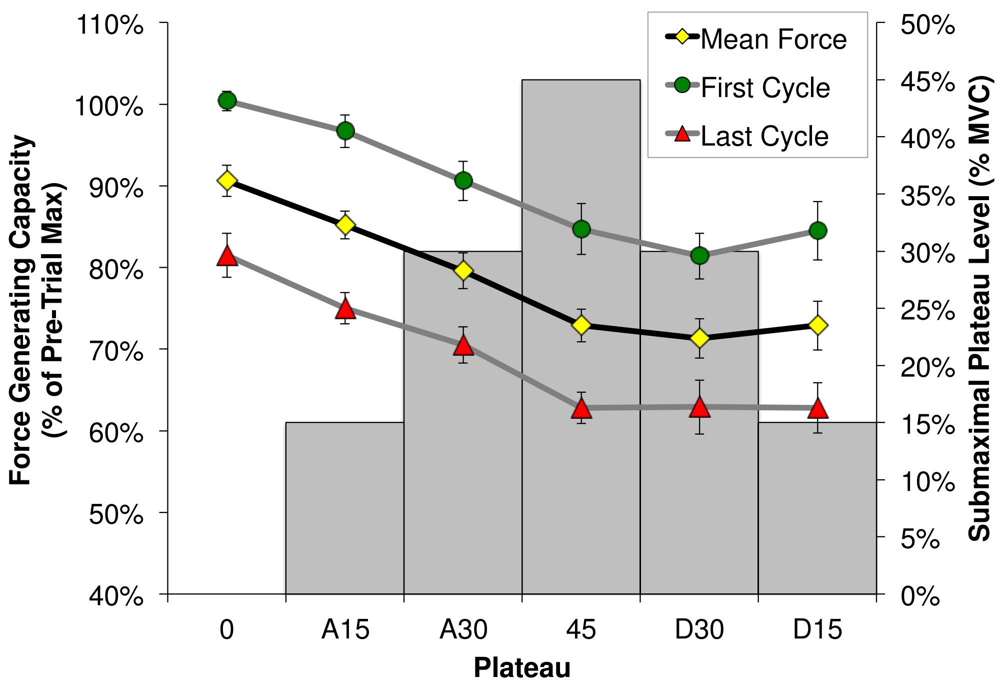

Figure 3.3. Average maximum strength (± standard error), as a percentage of the rested maximum, from the post-plateau grip forces (n = 10). The black line with yellow markers represent the mean strength collapsed across the first and last cycles. The strength after 0% was higher than that from A30% to D15%, and the strength at A15% was higher than that from 45% to D15% (both p<0.001). The strength at A30% was higher than that from 45% to D15% (p<0.01).

3.3.2 MEAN POWER FREQUENCY

Comparisons of MnPF between Cycle, Direction and Plateau were only considered between plateaus of the same grip MVC-relative force (15% MVC or 30% MVC plateaus at the beginning versus end of the cycle). For the MnPF of the BRD, there was a significant main effect of Cycle ($p < 0.05$) and Direction ($p < 0.001$) for both the 15% and 30% plateaus. BRD MnPF decreased from 114.4 ± 11.0 to 108.0 ± 13.2 Hz (5.6%), from the first to last cycle, for the 15 % MVC plateaus, and from 108.7 ± 11.3 to 103.2 ± 12.7 Hz (5.1%), from the first to last cycle, for the 30% MVC plateaus (Figure 3.4). Considering the main effect of Direction, the MnPF during the ascending plateau was significantly higher than the MnPF during the descending plateau (118.1 ±12.2 Hz compared to 104.2 ± 12.0 Hz for the 15 % MVC plateau, and 111.3 ±13.1 Hz compared to 100.6 ± 10.9 during the 30% MVC plateau).

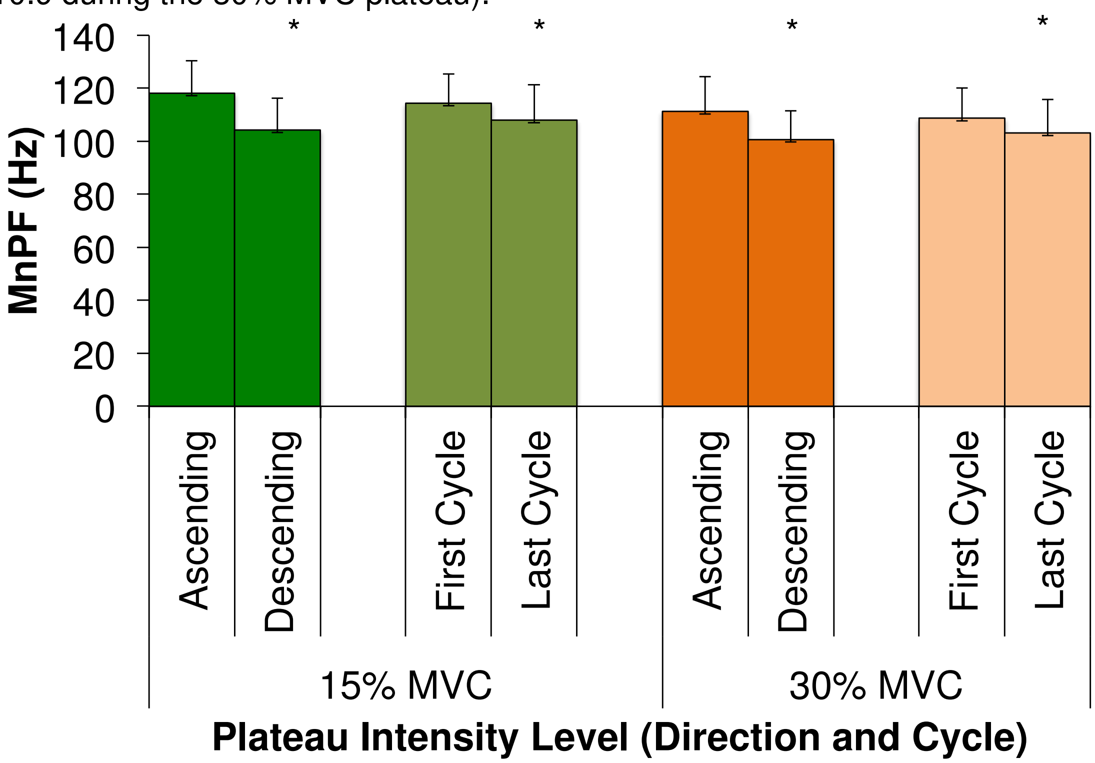

Figure 3.4. Mean power frequency (MnPF; Hz ± standard error) of the brachioradialis (BRD). Differences between the first and last cycle were found ($p<0.05$), as well as between the beginning and the end of the cycle during both the 15% MVC and 30% MVC plateaus. The * indicates a significant decrease ($p<0.05$).

There was a main effect of Direction for the FCU MnPF for both the 15% MVC and 30% MVC effort levels (both $p < 0.05$). FCU MnPF was 12.7 Hz lower during the descending 30% plateau (D15%), at 88.5 ± 17.1 Hz, compared to the ascending A15% plateau, at 101.3 ± 20.1 Hz. (Figure 3.5). Similarly, FCU MnPF was 12.5 Hz lower during the descending 30% plateau (D30%), at 84.5 ± 18.4 Hz, compared to the ascending A30% plateau, at 96.6 ± 18.4 Hz. (Figure 3.4).

3.3.3 AVERAGE EMG

As expected, BRD and FCU muscle activity increased with an increase in force demand during the submaximal plateaus. However, there were no significant effects of Cycle, Direction or Plateau for any of the aEMG dependent measures tested in the ANOVAs.

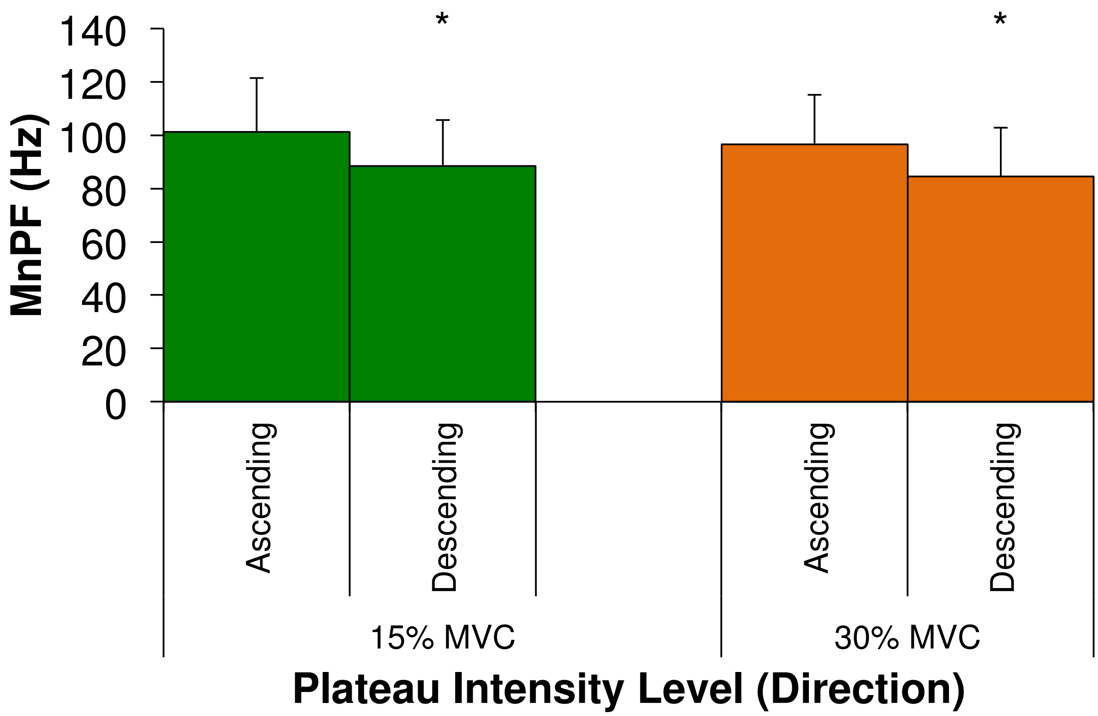

Figure 3.5. Mean power frequency (MnPF; Hz ± standard error) of the flexor carpi ulnaris (FCU) was significantly lower during the descending aspect of the plateau for both the 15% MVC and 30% MVC plateaus. The * indicates a significant decrease ($p<0.05$).

3.4.0 DISCUSSION

This study evaluated the effect of a complex effort-time history on the accumulation of fatigue during a handgrip task. Despite significant decreases in the post-plateau MVC grip forces during the ascending aspect of the pyramid, there were no significant changes on the descending side of the pyramid (Figure 3.2). Therefore, it would seem that the accumulation of fatigue, during a particular effort, was dependent on both the preceding MVC-relative force time-history and current status of the muscle. The A15% MVC plateau, that followed 0% MVC, resulted in a decrease in force production capacity. However, handgrip strength actually increased during the D15% MVC plateau, which followed a 30% MVC effort, even though it started in a more fatigued stated. This study suggests that both the preceding fatigue, and current demands, contribute to determine whether an effort will result in fatigue accumulation or, conversely, actually provide the opportunity for recovery.

A recent study by Yung et al., (2012) also found that the effort time-history affected fatigue accumulation, even if the average effort was consistent across conditions. Their participants completed various MVC-relative force patterns, all with an average demand of 15% MVC. In patterns where efforts were higher and lower than the average force, but did not return to 0% MVC, there was less fatigue accumulation than during a sustained isometric 15% MVC contraction. They also observed differences in blood flow velocity, between a sustained isotonic contraction of 15% MVC, and isometric contractions that alternated between 7.5% and 25.5% MVC. They postulated that some time at lower forces may allow for re-perfusion of the muscle, which supplies the muscle with energy substrates and rids the contraction by-products, allowing for a decreased rate of fatigue. Similarly, in our current study, the descending phase of the submaximal force pyramid (from 45% to 30% MVC and 30% to 15% MVC) may have allowed for a re-perfusion of the muscle and consequent maintenance, or even recovery, of maximum force generating capacity.

Post-activation potentiation (PAP) is another mechanism that could explain the change in the reduced rate of fatigue progression on the descending side of the cycle. PAP is the enhancement of muscular performance as a result of the muscle's contraction history (Tillin & Bishop, 2009). When the muscle performs a high intensity contraction, there is an increase phosphorylation of the myosin light chains, as well as a recruitment of larger motor units, that lead to increased tetanic force production (Tillin & Bishop, 2009). Sale (2004) found that PAP has the greatest effect when the type of task being performed requires smaller motor units, such as those that would be found in the forearm and used during this handgrip task. Additionally, Fukutani, et al., (2012) found that conditioning plateaus, of greater submaximal intensity, positively impacted the amount of potentiation in twitches that followed the effort. In an additional study by Fukutani et al., (2014) conditioning contractions, with intensities as low as 20 and 40% of MVC, evoked significant amounts of post-activation potentiation during a thumb adduction task. Fukutani et al., (2012) found that there was significant twitch potentiation resulting from preceding contraction intensities as 40% of MVC. However, there was no effect of conditioning contractions of less than 60% MVC on maximum voluntary forces. These results come from an experiment on plantar flexion of the ankle – so it is unknown if these results would change in the thumb adduction.

In our study, as participants decreased their effort from a submaximal plateau of 45% MVC, to the D30% plateau of lesser intensity, it is possible that PAP contributed to the decreased rate of fatigue on the descending aspect of the pyramid in the form of recovery of MVC strength. However, the PAP effect will eventually diminish, and give way to fatigue, resulting in a loss of force over time (Johnson et al., 2013). Since the fatigue criteria in our study was only a 35% reduction in MVC, PAP may still have been contributing to the recovery witnessed after the final 15% MVC plateau during the last fatigued cycle.

Based on the size principle (Henneman, 1952) the fast twitch fibres would not have been recruited (and consequently would not have fatigued) in the first 15% ascending plateau, but smaller motor units, which were initially recruited, would have become partially fatigued during these efforts. However, the faster twitch fibres would have been partially fatigued during the first 45% plateau. When the pyramid descended down to the 30% plateau, and eventually the descending 15% plateau, these faster twitch units would no longer be recruited and would be able to recover. It is likely that, during that 15% effort, the strength gains for the deactivated larger units led to more strength gain, than the strength lost in the smaller units recruited during the descending 15% efforts.

We observed a complex progression of the fatigue during sequential contractions with varying effort levels. Neuromuscular fatigue is a continuous process, and results from an interaction of central and peripheral factors (Boyas & Guével, 2011; Gandevia, 2001). Central fatigue factors decrease the voluntary activation of the muscle, either by decreasing the central command from the primary motor cortex or by modulating the propagation of the signal down the pyramidal pathways or the activation of the motor units themselves (Gandevia, 2001). Peripheral fatigue factors diminish the contractile strength of the muscle fibres resulting from alteration of the mechanisms involved in the transmission of the action potentials (Boyas & Guével, 2011). Central and peripheral factors can be monitored in various ways, but the presence of neuromuscular fatigue in the present study was monitored by EMG amplitude and mean power frequency, in addition to the capacity for maximal voluntary force production that provides an overall evaluation of fatigue status. However, changes in the spectral characteristics of the EMG signal provide more insight into the peripheral fatigue mechanism, reflecting the decrease in the speed of propagation of the action potential as the result of biochemical changes to the intra and extracellular environment of the muscle fiber (Boyas & Guével, 2011; Frey Law & Avin, 2010). We observed decreases in force production from the first to last cycle, and this was paralleled by decreases in mean power frequency of the BRD and FCU, during both the 15% MVC and 30% MVC plateaus, at the end of cycle compared to the beginning, both confirming the presence of fatigue.

Interestingly, there were no significant changes in aEMG between ascending and descending 15% or 30% MVC plateaus. While it could be expected that significant changes in EMG would accompany the 35% decrease in maximum grip force capacity, there are two reasons why this may not have been observed. First, we looked at AEMG from across the 15 second plateau, it is possible shifts in EMG amplitude that would occur in particular at the end of the 15 second plateau, just prior to eliciting the maximum contraction, are being somewhat masked by this average. Additionally, the larger motor units, which were likely engaged during the 45% MVC plateau and the maximum voluntary grip efforts at the end of each plateau, would have been the first to fatigue. Given that we made comparisons only between the 15% and 30% plateaus, the fatigue of these larger units would not be a factor in the lower level submaximal contractions. The purpose of the study was to examine the effect of the time history of forces on the accumulation of fatigue. Therefore we felt it was best to focus our examination on differences between like efforts that were preceded by either a higher or lower relative effort.

The fatigue criteria for this study were: i) a drop of 35% MVC in grip force generating capacity during the post plateau maximum efforts or, ii) the inability to sustain the requested submaximal force. Most trials were terminated because of the first fatigue criteria and were not yet to the point of not being able to sustain the submaximal forces. Therefore, it is possible that the demands of the submaximal plateaus were enough to result in slowing propagation (Boyas & Guével, 2011; Frey Law & Avin, 2010) and perhaps synchrony of the active motor units (Gandevia, 2001), seen as the shift in MnPF, but not yet great enough to require the recruitment of additional motor units. It is also possible that activation switching between muscles in the forearm occurred to provide addition force and support the FCU during the handgrip task, thus not necessitating greater output from the FCU itself.

There are some limitations to this study. Not unlike Byström & Fransson-Hall, (1994), complete rest was given during this study after the post-plateau maximal grip efforts. Although full rest is often not provided in industrial tasks, we provided it briefly after each plateau, to partially counter any fatigue affects caused by the post-plateau MVC's, which were used to monitor fatigue progression but were not intended to contribute to fatigue. Maximal efforts are not common in the workplace. The distribution of the submaximal plateau force were in a pyramid, so that we could determine if the fatigue occurring over the duration of a plateau, preceded by a lower force, differs from that preceded by a higher force. However, this would not be a typical pattern of force distribution in an industrial setting and, therefore, a more randomized pattern should be examined in the future.

The effect of an aging work force has become an ever more prevalent question in ergonomics. Age-related changes to muscle, such as sarcopenia, increases in intramuscular fat, decreases in the number of motor units, and a loss of type II fast-twitch fibres (Deschenes, 2004), results in a greater proportion of the muscle being type 1, slow twitch fibres. These fibres are more fatigue resistant, which has been shown to increase the endurance in an older population compared to a younger population during submaximal contractions (Hodder et al, 2014). Therefore, the population used for this study (university aged females) may someone limit the applicability to other populations. Future research should examine the force history effects of fatigue in older populations, as well as males.

Yung et al., (2012) examined fatigue accumulation in different trials with different force variation patterns. As a result, the preceding effort was always the same (be it 0%, 1%, 7.5% MVC, etc.,). Their findings were important to show that fatigue accumulation within cycles that consisted of the same average force level was significantly impacted by the amount of variation in the force pattern. In our study, we examined how fatigue accumulated instantly within a cycle based on the factor of different force levels (in this case, MVC levels of 0, 15, 30 and 45% MVC). Our study shows that the immediately preceding force level has an instantaneous impact on the level of fatigue in a task, where as the findings from Yung et al., 2012 indicate that at the end of a cycle, fatigue levels are altered by the variation of forces.

3.5.0 CONCLUSION

We observed differences in fatigue accumulation during the ascending and descending phases of the force pyramid. When preceded by a greater force requirement, a sustained effort of 30% MVC did not significantly contribute to fatigue accumulation. Furthermore, a 15% MVC effort actually allowed for a recovery in force generating capacity with respect to previous maximum efforts when preceded by a more difficult effort. We conclude that, in a pattern of contractions of ascending then descending force intensity, voluntary force recovery was present when the preceding force was of a lower intensity. These findings make it important to account for the preceding demands when determining the amount of fatigue that will accumulate during complex tasks.

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CHAPTER 4:
Fatigue Accumulation and Twitch Potentiation During Complex MVC-Relative Profiles

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ABSTRACT

Fatigue accumulation can be significantly influenced by post-activation potentiation (PAP). This phenomenon leads to increased force generating capacity after a series of conditioning efforts (Sale, 2004). The purpose of our study was to examine how the order of force demands impacted muscle fatigue accumulation, and how fatigue was affected by potentiation. We had 33 participants complete one of four different force orders, consisting of 5 cycles of 12-second submaximal isometric “task plateaus”. Every order consisted of 8 force plateaus of the different intensity, arranged in a different ways. A subset of 18 participants then received a stimulated muscle twitch, and all participants performed a brief MVC. Each task plateau was followed by a 12 second long 10% MVC “reference plateau” also followed by twitch and MVC. Overall, the order of the force presentation only had an impact on fatigue levels and twitch potentiation during the first cycle. At the end of each cycle, there was no difference between any of the orders in terms of twitch potentiation or decrease in MVC force. In a task that features identical force patterns, arranged in different orders, the order did not affect the final fatigue accumulation.

Keywords: Neuromuscular fatigue, twitch potentiation, force time history

4.1.0 INTRODUCTION

Manufacturing assembly lines typically require workers to perform a series of subtasks, with varying force demands. Each of these demands is essential to the performance of the overall job, and the final quality of the end product. Repetitive work can lead to muscle fatigue (Björkstén and Jonsson, 1977; Hagberg, 1981; Potvin, 2011; Vøllestad, 1997), which has been shown to reduce performance (Gates and Dingwell, 2008), decrease quality of work (Dan et al., 2010; Lin et al., 2001; Wartenberg et al., 2004) and, be correlated with the development of musculoskeletal disorders (Allan, 1998; Dugan and Frontera, 2000; Sjøgaard and Søgaard, 1998) Ergonomists have a set of tools that they can use to evaluate repetitive work. However, many of these tools assume that all of the efforts are of equal intensity and duration, and are followed by complete rest periods of equal duration (Rohmert, 1973; Potvin, 2012).

4.1.1 MECHANICAL EXPOSURE VARIATION

Yung et al. (2012) studied 15 male participants performing elbow extension efforts with an average demand of 15% MVC including a sustained isometric contraction at 15% MVC, a sinusoidal pattern from 0% to 30% MVC (6 cycle) and three intermittent patterns with equal 2.3 s durations of a low value and a high value, and a 0.7 s transition between plateaus, including patterns with low and high values of: a) 0% and 30% MVC, b) 7.5% and 22.5% MVC, and c) 1% and 29% MVC. The reduction in force capacity, for each force pattern, was only one of nearly 30 measures made in their study, including EMG, MMG, blood lactate measures and endurance time. They found that there was a continuum of fatigue responses for the five exertion patterns, even though they all had the same average demand. On further analysis, we determined that the endurance times had an increasing curvilinear relationship with the standard deviation of the effort (about the 15% mean), and increased from its lowest duration of 579 s with the 15% sustained contraction (SD = 0%) to 1474 s with 7.5-22.5% (SD = 7.5%) to 2205 s with 0-30% sine (SD = 10.6%) to 3202 s with 1-29% (SD = 14.0%) to the limit of 3600 s with 0-30% (SD = 15.0%). Their findings demonstrated that modifying the time-history of a force demands, about an average force level, might be an effective method for reducing the rate of fatigue during work. These findings also illustrated that using the average force level, within a cycle, may not accurately reflect the potential for fatigue accumulation during a task. It should be noted that fatigue measurements of MVC, twitch force and low frequency fatigue were taken every 15 minutes during the exercise protocol, so it is unknown how these additional demands affected the force generating capacity at specific time points within a complex MVC-relative history.

4.1.2 COMPLEX MVC-RELATIVE HISTORY AND FATIGUE ACCUMULATION

Sonne et al., (2014) studied 10 female participants as they performed a handgrip task that consisted of 6 submaximal force plateaus, each for 15 s, in a pyramid cycle of 0, 15, 30, 45, 30, and 15% MVC. This was repeated for as many cycles as possible, until they could no longer sustain two consecutive plateaus, or their MVC force level dropped below 65% MVC. After each plateau, the participants performed a brief MVC, and the strength loss, relative to the rested strength, was determined to be the fatigue level at that time. Participants completed between 2 and 3 cycles of the task. There were significant increases in muscle fatigue as participants ascended the force pyramid. However, there was no significant fatigue accumulation as they went from the 45% plateau, at the top of the pyramid, and descended to lower force levels. In fact, during the second half of the first cycle, there was actually a decrease in fatigue during an MVC after a 15% MVC plateau that followed a 30% MVC plateau. The fatigue resistance observed, as efforts decreased from higher levels, may have been caused by post-activation potentiation (PAP). PAP is an activity-dependent increase in isometric twitch force, which can cause an amplified level of myosin cross bridge activity in response to submaximal concentrations of myoplasmic calcium (Sale, 2004). This phenomenon can lead to increased force generating capacity in the muscle, after a series of conditioning plateaus. PAP is evident up until the point when the effects of muscle fatigue overcome the benefits of PAP, and muscle strength begins to fall (Rassier and Macintosh, 2000). This phenomenon could explain why the MVC forces increased when following submaximal plateaus of greater intensity in the first cycle of the force pyramid (moving from force levels of 45% MVC to 30% and 15% MVC) but, during the final cycle, all forces remained depleted and in a fatigued state. It is unknown how robust this potentiating effect would be during a more complex force pattern, or how much the effect of potentiation would have on a MVCs performed after different submaximal plateau levels.

4.1.3 PURPOSE

The purpose of this study was to determine: 1) the influence of the force demand time-history on fatigue accumulation during different tasks with identical duty cycles and average forces. 2) the effects of effort intensity, of the preceding plateau, on fatigue accumulation rates during a standardized effort of a given intensity level. 3) the potential role of potentiation during complex force time-histories.

4.2.0 METHODS

4.2.1 SUBJECTS

After approval from the university's research ethics board, we recruited 33 female participants from the undergraduate and graduate student populations, free of injury to the right arm in the past year (mean ± SD of all participants – 166.5 ± 9.1 cm; 63.1 ± 11.5 kg; 24.8 ± 3.2 years). Of the 33 female participants completing a fatigue protocol, a subgroup of 18 also performed a stimulation protocol during the experiment. We assigned all 33 participants to one of four experimental force-profile orders. This will be described in more detail later. Demographic and anthropometric information is provided for each group Table 1.

Table 4.1. Participant anthropometric and demographic information between all four experimental orders for all participants (n = 33).

Order	Age (Years)	Height (cm)	Weight (kg)	n (total)	n (w/ twitch)
0-15-30-45	25.8 ± 4.9	168.4 ± 6.9	63.7 ± 13.4	8	5
15-45-0-30	22.3 ± 0.6	169.2 ± 5.4	66.1 ± 12.9	8	4
30-0-45-15	25.4 ± 2.9	164.6 ± 12.5	62.4 ± 10.7	9	5
45-30-15-0	25.5 ± 2.3	163.7 ± 9.9	61.8 ± 10.7	8	4

4.2.2 DATA ACQUISITION AND INSTRUMENTATION

4.2.2.1 FORCE

Each participant was custom fit to a thermoplastic brace (Patterson Medical, Mississauga, ON), which held the hand in a neutral posture, with the thumb abducted 45 degrees with respect to the first metacarpal. A ring, covered with thin foam and electrical tape (to provide comfort for the participants), was attached to an S-type load cell (100lb max, Omegadyne Inc., Laval, QC, Canada). The position of the load cell was adjusted so that the mass of the distal segment of the thumb was supported by the ring, and the ring contacted the digit in the centre of the pad of the thumb. The strain gauge was mounted on an aluminum frame constructed of slotted rail (80/20 Inc., Columbia City, IN). The experimental set up allowed for adjustment of the height of the strain gauge to fit each participant's hand. Prior to collection, the force bias was subtracted to account for the mass of the thumb. Force data were sampled at 2000 Hz, and collected in custom LabView software (National Instruments, Austin, TX).

4.2.2.3 STIMULATION

To determine the impact of potentiation on force generating capacity during the protocol, 18 participants (randomly assigned) had an indwelling tungsten electrode inserted into their FPL. A stimulation procedure, similar to Fuglevand et al. (1999), was used to maximally drive the FPL. A sterilized tungsten microelectrode (shank diameter = 250 micrometers, epoxylyte insulation, impedance = 50 - 100 kΩ, Frederick Haer & Co., Bowdoin, ME, USA) was inserted into the skin on the medial side of the forearm, directly into the belly of the FPL. An adjacent electrode was placed on the lateral epicondyle of the elbow to serve as the anode. The electrode was connected to a Digitimer constant current stimulator (model DS7A, Letchworth Garden City, UK). A Digitimer trigger interfaced with the stimulator to control the frequency, duration and delay on the delivery of the stimulation.

4.2.3 EXPERIMENTAL PROCEDURES AND PROTOCOL

On the first day of the experiment, participants read and signed an informed consent form, were fit to a custom thermoplastic brace and then performed a training protocol. The training protocol consisted of a series 12 second long submaximal plateaus, at intensity levels of 0, 10, 15, 30 and 45% MVC, which were each followed by a 2 second rest break, a 2 second MVC, and 2 seconds of rest. The purpose of the training protocol was to make the participants familiar with going from the submaximal plateau to complete rest, then ramping back up to their MVC. The practice trial was approximately 10 minutes long. Participants were given at least 24 hours before the testing session of the experiment. If they reported any form of discomfort or decreased ability to perform the task, they were given additional time in between their training and testing day. During the testing session, participants were seated in an ergonomic office chair adjusted to their own dimensions. The armrest was adjusted so the shoulder was relaxed, and the forearm was in line with the experimental apparatus. A piece of foam was placed under the participant's hand for comfort.

4.2.3.1 PROTOCOL – WITH STIMULATION

For the participants receiving stimulation, the skin on the forearm was cleaned with 90% alcohol. The forearm was palpated to find the belly of the FPL. The experimenter then inserted the tungsten electrode percutaneously and into the belly of the muscle. Doublets of low intensity (500 µs in width, spaced 50 ms apart) were delivered to confirm the electrode placement. Proper placement was marked by a distinct flexion of the distal joint of the thumb with little, to no, discomfort reported by the participant. Once the position was confirmed, the intensity of the stimulation was gradually increased to elicit the maximum stimulation response. When the force generated by the stimulation no longer increased, the intensity of the stimulation was increased an additional 25%.

Maximum FPL activation and maximum voluntary contraction efforts were collected during the same trial. The participant was asked to perform maximum isometric efforts of the distal interphalangeal joint of the thumb against the strain gauge three times for 3 seconds, spaced 60 seconds apart. Surface EMG of the FPL was recorded during these trials. Immediately after the MVCs, and the participant's return to rest, a supramaximal twitch was delivered and the force response was recorded as the pre-trial potentiated twitch value.

4.2.3.2 PROTOCOL WITH AND WITHOUT STIMULATION

MVCs were performed with the participant maximally flexing the thumb isometrically against the strain gauge three times for 3 seconds, spaced 60 seconds apart. There were four separate MVC-relative profiles created, consisting of different orders of isotonic "task" plateau presentation (at 0, 15, 30 and 45% MVC). Each isometric plateau was 12 seconds in duration. After the plateau, there was a 2 second rest break, where participants were instructed to relax completely. Those participants receiving a supramaximal twitch would receive it at this time (Figure 4.2), and those who did not were able to rest during this period. Participants were then instructed to perform an MVC, ramping their effort up to maximum over the course of the two-second window, before returning to rest for another two seconds, and then starting the next submaximal, isotonic plateau. Each task plateau was paired with a 10% MVC "reference" plateau (see Figure 4.1), such that each cycle consisted of 4 task plateaus followed by a 10% reference plateau. The cycles were all (12 + 2 + 2 + 2 s) x 8 plateaus = 144 seconds. The plateau orders were: 0-15-30-45% MVC (0% then 15% then 30% then 45%), 15-45-0-30% MVC, 30-0-45-15% MVC, and 45-30-15-0% MVC. Participants were block randomized and evenly distributed into one of the four plateau order conditions. Each performed 5 cycles of their plateau order condition.

4.2.4 DATA ANALYSIS

4.2.4.1 FORCE DURING THE PLATEAUS

Force signals, recorded during the plateaus, were smoothed with a half second moving average. The voltage outputs from the force gauge was converted to Newtons, and then normalized to the participant's pre-trial, rested MVC. The MVC after each plateau was compared to the pre-trial MVC.

4.2.4.3 TWITCH ANALYSIS

Forces, recorded during the twitches, were filtered using a 20 Hz low pass Butterworth filter. The peak tension (PT) was calculated by determining the maximum force after the stimulation was delivered. The exponential relaxation time (eRT) was calculated as the duration from peak tension to when force relaxed to 20% of the peak. This period has been determined to be that where the relaxation curve most closely resembles an exponential function (Woittiez et al., 1984).

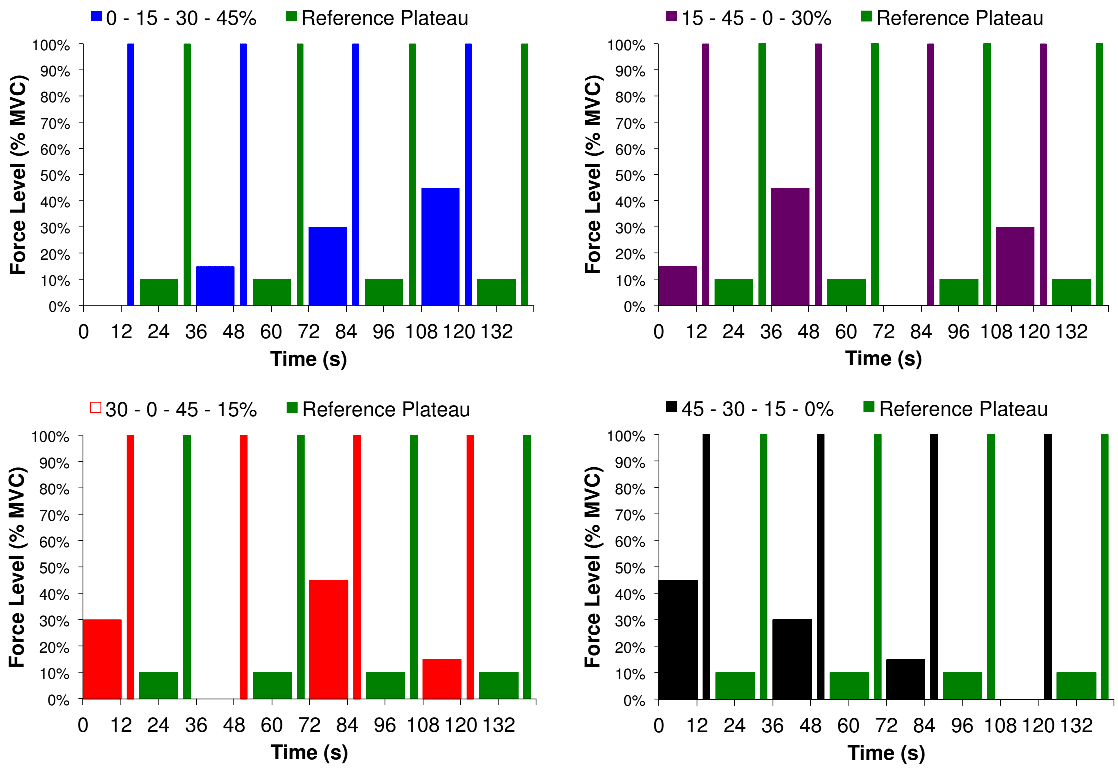

Figure 4.1. The experimental conditions consisted of a 12 second submaximal plateau of an intensity of 0, 15, 30 or 45% MVC, followed by a twitch (within a 2 second window), a brief (2 second) MVC, and 2 seconds of rest (duration = 18 s). Each submaximal plateau was followed by a 12 second 10% MVC reference plateau (with twitch, MVC and rest periods, duration = 18 s). Four different submaximal plateaus, with four 10% reference plateaus, comprised one cycle (duration = 144 s), and each participant completed 5 cycles of a condition, such that each experimental trial was 720 s (12 mins) in duration.

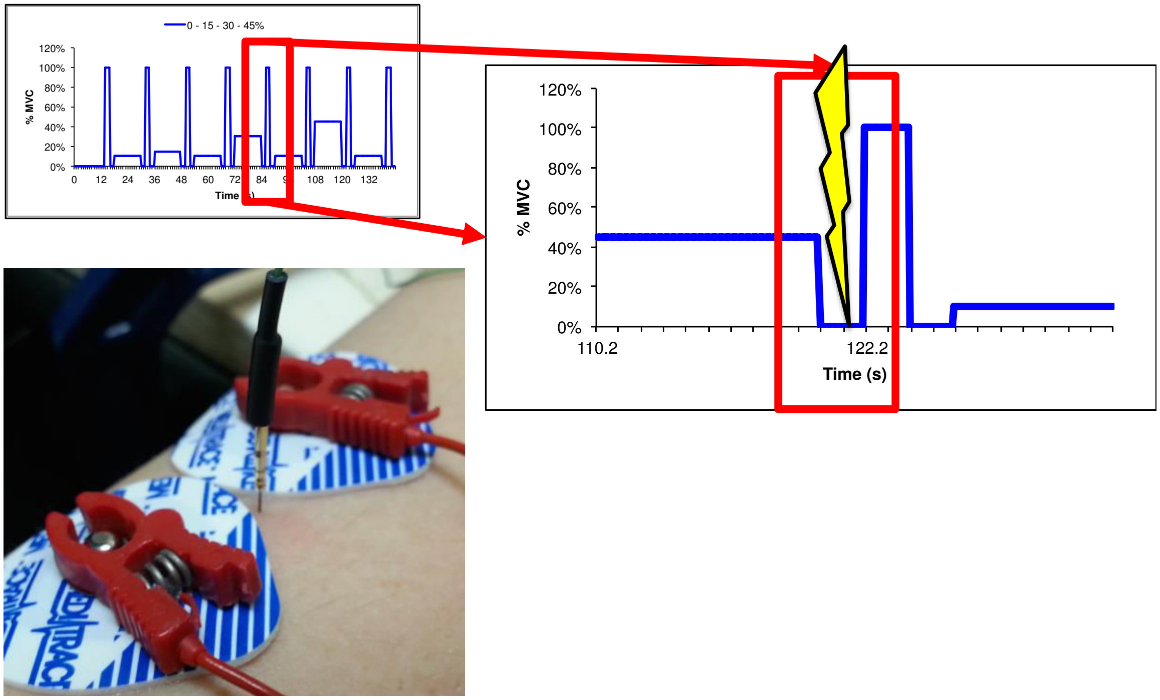

Figure 4.2. In trials where participants received stimulation, a tungsten needle electrode was inserted into the FPL through the skin of the forearm. Participants completed a plateau with an intensity between 0 and 45 %MVC for 12 seconds, then returned to rest. At this point, stimulation was delivered to the muscle to evoke a twitch. The force of the twitch was measured to indicate the degree of potentiation the muscle was experiencing.

4.2.4.4 PLATEAU ANALYSIS

To examine the effect of the effort time-histories, the MVC forces and twitch statistics were coded to be in the order of 0, 15, 30 and 45 %MVC regardless of the order they were performed during the experimental trial. Statistical analyses were performed on the following comparisons: 1) the change in value during the task plateau, based on a comparison of the MVCs, or twitch forces, recorded before and after the task plateau, and 2) the change in value during the reference plateau, based on a comparison of the MVCs, or twitch forces, recorded before and after the reference plateau (Figure 4.3).

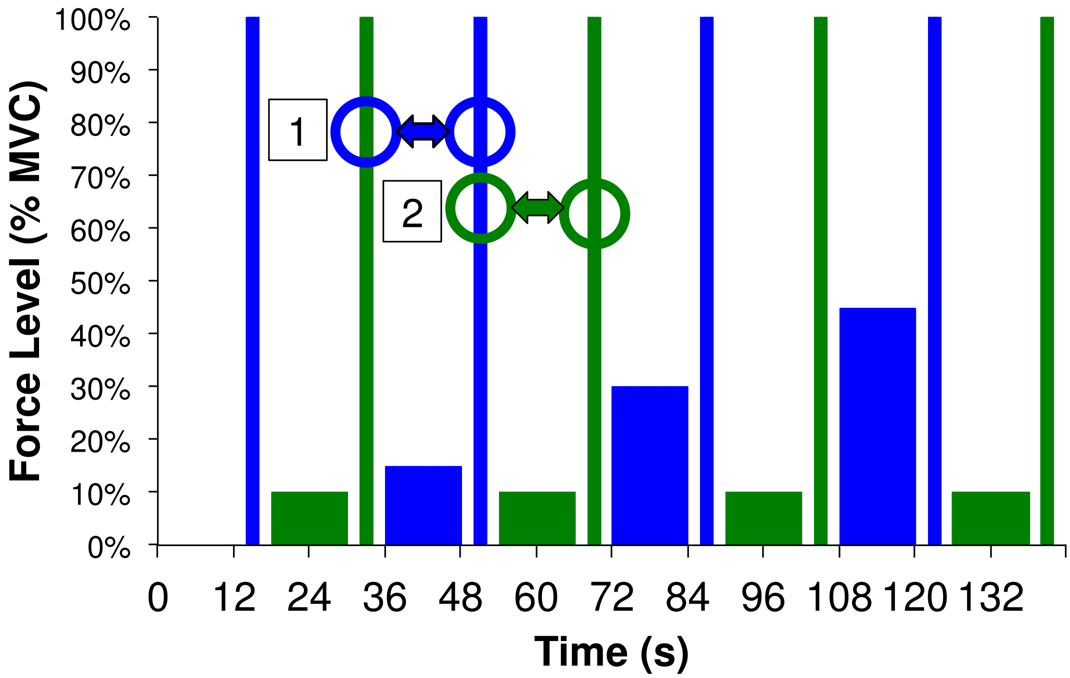

Figure 4.3. Changes in the MVC force, Twitch force, and exponential relaxation time were examined during the change during a task plateau (1. blue circles), and change during a reference plateau (2. green circles).

4.2.5 STATISTICAL ANALYSIS

A 4 x 5 x 4 mixed measures ANOVA was used to examine the changes in values occurring during both the task plateaus and the reference plateaus. The independent variables were the between variable of order (n = 4) and the within variables of cycle (n = 5) and plateau (n = 4). An additional 4 x 5 mixed measures ANOVA was used to examine changes in the dependent variables after the final reference plateau in each cycle. The independent variables were the between variable of order (n = 4) and the within variable of cycle (n = 5). For all ANOVAs, the dependent variables were MVC force, peak twitch force, and exponential relaxation time. All significant main effects and interactions were evaluated with Tukey's HSD post hoc tests, with significance set to $p < 0.05$.

4.3.0 RESULTS

4.3.1 MVC FORCE

The mean (SE) MVC force across all 5 cycles was 79.4 ± 10.4% for order 0-15-30-45, 75.5 ± 11.4% for order 15-45-0-30, 76.3 ± 10.8% for order 30-0-45-15, and 76.0 ± 9.9% for order 45-30-15-0. All participants were able to complete the full 5 cycles of the trial.

4.3.1.1. CHANGE DURING THE TASK PLATEAUS

There was a significant interaction between plateau and order ($p < 0.001$) for changes in strength during the task plateaus (Figure 4.4). However, post hoc tests revealed no differences between orders at any plateau. There was also a significant interaction between cycle and plateau ($p < 0.001$). Cycle 1 elicited significantly more decrease in MVC during the 0% task plateau in the first cycle, compared to all other cycles (Figure 4.5). There was an average decrease of 8.92 ± 2.09 %MVC during the 0% MVC task plateau in the first cycle, compared to a 1.44 ± 1.49 % MVC decrease during the second cycle; a 0.11 ± 1.07 % MVC increase in the third cycle, a 1.65 ± 1.12 % increase in the fourth cycle, and a 2.45 ± 1.26 increase in MVC force during the fifth cycle.

4.3.1.2. CHANGE DURING THE REFERENCE PLATEAUS

There was a significant interaction between plateau and order ($p < 0.001$) for changes in strength during the reference plateaus. However, the post hoc analysis revealed no significant differences between orders at any cycle.

4.3.1.3. MVC DURING EACH CYCLE'S FINAL REFERENCE PLATEAU

There were no significant main effects or interaction effects of order ($p > 0.05$). There was a significant main effect of cycle on MVC force ($p < 0.0001$). MVC forces dropped significantly between cycles 1 and 5 (83.4 ± 1.7 % MVC compared to 71.1 ± 1.7 % MVC).

4.3.2 – PEAK TWITCH FORCE

The average peak pre-trial twitch forces (± SD) were 5.2 ± 1.5 N for order 0-15-30-45, 6.8 ± 2.2 N for order 15-45-0-30, 9.9 ± 5.3 N for order 30-0-45-15, and 6.3 ± 2.5 N for order 45-30-15-0. The mean (SE) peak twitch force (as a percentage of the pre-trial maximum) was 121.3 ± 12.0% pre-trial maximum for order 0-15-30-45, 116.2 ±16.7% for order 15-45-0-30, 86.5 ± 8.2% for order 30-0-45-15, and 85.2 ± 10.1% for order 45-30-15-0.

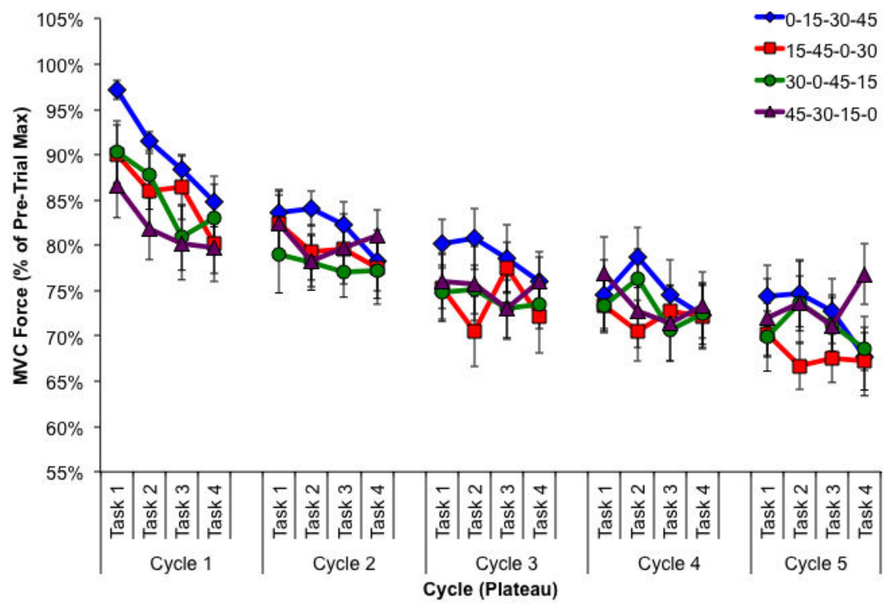

Figure 4.4. Average MVC force (± SE) from all 4 experimental orders following each of the 4 submaximal task plateaus over 5 cycles (n = 33). In the ANOVAs associated with the change in force between plateaus, the task and reference plateau pairs were all coded to be in the sequence of 0-15-30-45 (for example, the graph above would be re-ordered from task 1, 2, 3 and 4, to 0-15-30-45.

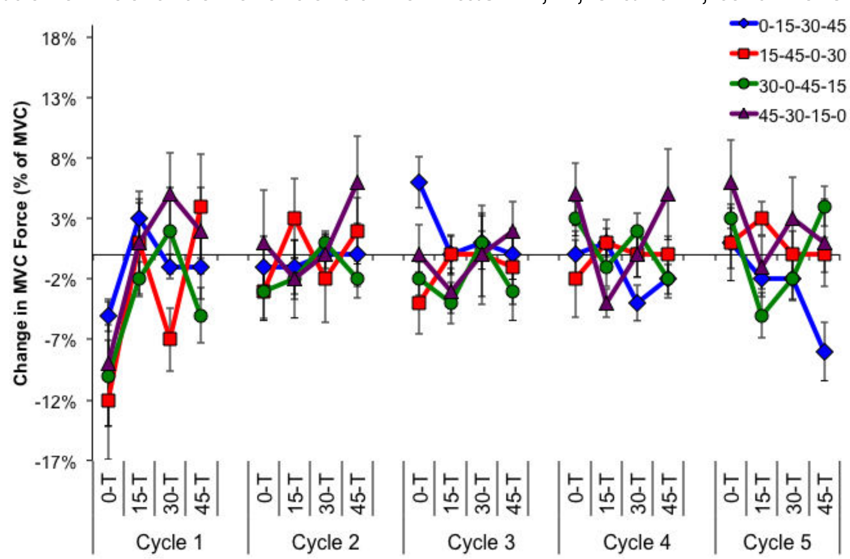

Figure 4.5. Average MVC force change (± SE) during the task plateaus (n=33) during the 5 cycles of the experimental protocol. There were significant differences between plateau intensities. Significant differences existed between the 0% task plateau and all other task plateaus during cycle 1, irrespective of the plateau order.

4.3.2.1 – CHANGE DURING THE TASK PLATEAU

There was a three-way interaction between cycle, plateau and order for the change in peak twitch force during the task plateaus. The significant differences in peak twitch force changes (as a percentage of pre-trial maximum twitch) occurred only within the first cycle of the protocol. These occurred between the 0-15-30-45 and 15-45-0-30 orders during the change in 0% (-22.6 ± 12.2% and 30.5 ± 13.7 %, respectively) and 15% task plateaus (18.4 ± 5.6% and -48.3 ± 6.3%, respectively). There were significant differences between the 15-45-0-30 order and the 30-0-45-15 order during the 15% task plateau (-48.3 ± 6.3% and -0.8 ± 5.6%, respectively) and the 30% task plateau (39.7 ± 15.7%, -27.2 ± 14.0, respectively). There was a significant difference between order 15-45-0-30 and order 45-30-15-0 during the 15% (-48.3 ± 6.3%, and 12.3 ± 6.3%, respectively) and 30% task plateau (39.7 ± 15.7 and -22.8 ± 15.7%, respectively) (Figure 4.6).

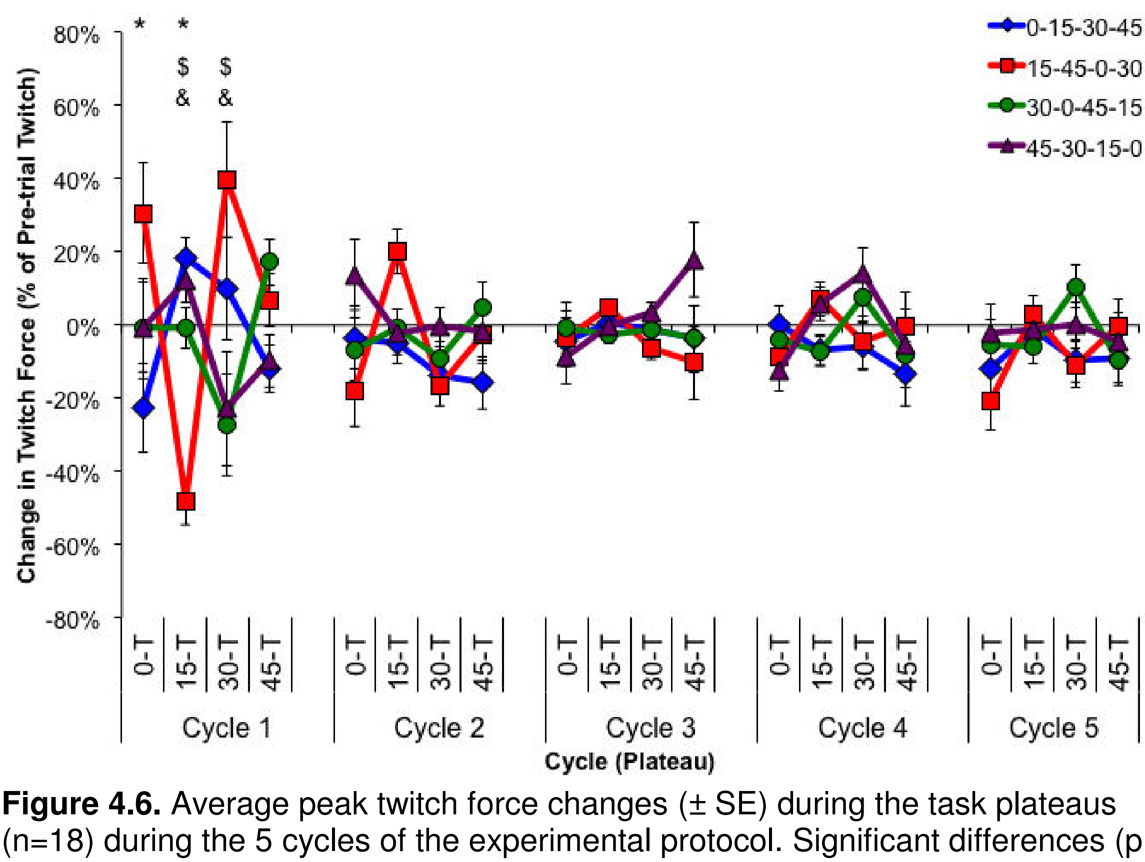

Figure 4.6. Average peak twitch force changes (± SE) during the task plateaus (n=18) during the 5 cycles of the experimental protocol. Significant differences ($p < 0.05$) between orders occurred only during the first cycle, between order 0-15-30-45 and order 15-45-0-30 (*), order 15-45-0-30 and order 30-0-45-15 ($) and order 15-45-0-30 and order 45-30-15-0 (&).

4.3.2.2 CHANGE DURING THE REFERENCE PLATEAU

There was a significant interaction between cycle, order and plateau ($p < 0.001$). The change in peak twitch (as a percentage of the pre-trial maximum), during order 0-15-30-45, was significantly different than order 45-30-15-0 during the 0% reference plateau (27.2 ± 7.7% and -6.2 ± 8.6%, respectively) during the first cycle. Order 15-45-0-30 was significantly different than 30-0-15-45 during the 15% reference plateau (31.5 ± 8.5% and -5.0 ± 7.6%, respectively); as well as order 45-30-15-0 during the 15% (31.5 ± 8.5, -5.0 ± 7.6%, and -2.0 ± 8.5%, respectively) (Figure 4.7).

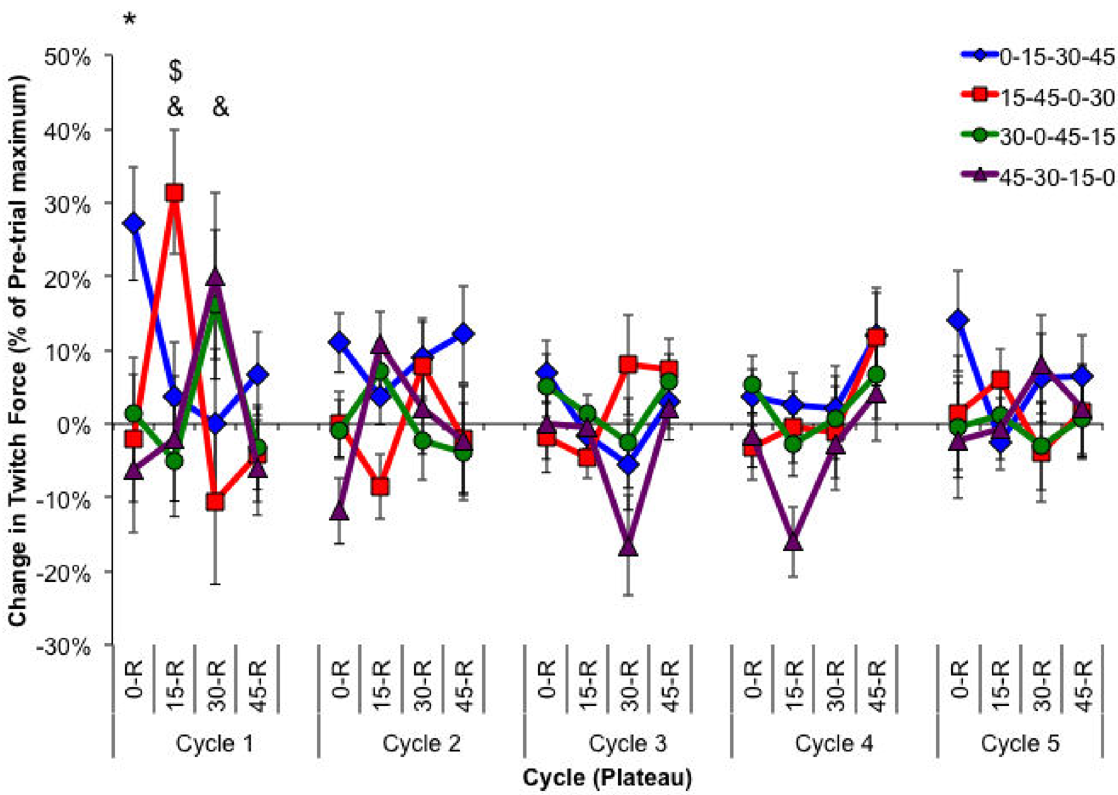

Figure 4.7. Average peak twitch force changes (± SE) during the reference plateaus (n=18) during the 5 cycles of the experimental protocol. Significant differences ($p < 0.05$) between orders occurred only in the first cycle, between order 0-15-30-45 and order 45-30-15-0 (*), order 15-45-0-30 and order 30-0-15-45 ($), and order 15-45-0-30 and order 45-30-15-0 (&).

4.3.2.3. PEAK TWITCH FORCE DURING EACH CYCLE'S FINAL REFERENCE PLATEAU

A significant main effect of cycle existed for the dependent variable of peak twitch force during the final reference plateau of each cycle. There was no significant interaction between the Cycle and Order. As a percentage of the pre-trial maximum, Cycle 1 (115.2 ± 24.3%) had significantly higher twitch forces than cycle 3 (104.6 ± 19.7%), cycle 4 (94.8 ± 19.7%), and cycle 5 (87.4 ± 16.9%). In addition, the post hoc revealed that cycle 2 had higher peak twitches than cycle 4 and cycle 5, and cycle 3 had greater forces than cycle 5.

4.3.3 EXPONENTIAL RELAXATION TIME

4.3.1.1 CHANGE DURING THE TASK AND REFERENCE PLATEAU

There were significant interactions between plateau and order for the change in ERT during the task plateau ($p < 0.001$) and the reference plateau ($p < 0.05$). However, post hoc test revealed no significant differences between orders at any plateau intensity level.

4.3.1.2 ERT DURING EACH CYCLE'S FINAL REFERENCE PLATEAU

There was a significant main effect of cycle on the ERT after the final reference plateau of each cycle ($p < 0.05$). Twitches following the final reference plateau of Cycle 1 had significantly lower ERTs than the final twitch in cycle 5 (0.081 ± 0.004 seconds and 0.091 ± 0.005 seconds, respectively).

4.4.0 DISCUSSION

This study demonstrated that there was a small effect of the task force plateau intensity on the amount of fatigue that accumulated in the reference plateau. There was never a significant main effect or interaction involving order during the final reference plateau of any cycle, indicating that the order of plateaus did not have an effect on the overall fatigue level. Any changes that were significant, as a result of the order of plateau combinations, appeared to happen during only the first cycle of the task. Significant changes in the peak twitch force, as a result of plateau order, all happened in the first cycle, which is consistent with our hypothesis that the changes in force generating capacity in Sonne et al., (2014) were due to post activation potentiation. After the first cycle, changes in potentiation between orders appeared to subside, and twitch force dropped in parallel with MVC force.

Job rotation is one method used to reduce fatigue in the workplace. This involves moving employees between different tasks, to prevent over-loading one muscle group. Luger et al, (2014) performed a meta-analysis on the effects of temporal (work-rest ratios) and activity (job-rotation) variation on fatigue accumulation. Of the seven studies that used activity variation, only Yung, Mathiassen, & Wells, (2012) found more than one objective measures (EMG, MMG, MVC, etc.), which proved that exposure variation significantly changed fatigue accumulation in a task. The remaining studies presented contradictory information on the effect of rotating between tasks, and the impact it had on muscle fatigue. Subjective measures, such as perceived exertion, arousal and pain, were improved by increased exposure variation in 4 of the 6 studies in the meta analysis, though in the two studies from the analysis, perceived discomfort and exertion both increased. These conflicting reports, regarding the effects of job rotation and exposure variability on fatigue accumulation, are comparable to our findings that there is a negligible effect of the order of tasks on how fatigue accumulates.

Our study demonstrated little effect of the MVC-relative history on how fatigue accumulated during the course of a task. Force time-history effects were examined using four plateau orders that featured identical average forces, force variation and rest times. Keir et al., (2011) investigated the influence of rotating between different combinations of lifting and gripping tasks, on the accumulation of fatigue. Rotating the tasks had significant effects on the muscle activity in the back and forearms. However, there were no significant differences between the tasks that involved both lifting and gripping, with the tasks presented in a different order. In Keir et al (2011), the impact of time-histories of forces on muscle fatigue levels may have been significantly impacted by the high percentage of rest that participants had within their cycles (a 5 second on, 5 second off cycle). Fatigue accumulation may have also been significantly altered by the long duration of each task during the cycles (15 minutes, prior to moving to the next task). Regardless, the order of the tasks used by Keir et al., (2011) did not play a large role in the accumulation of fatigue they observed, which is comparable to the results reported in our current study. From an ergonomist's perspective, the order of tasks may play a role in how fatigue accumulates after efforts of a specific intensity, but the overall fatigue accumulation may not be impacted by the order of these efforts within a cycle.

During repetitive submaximal tasks, such as those seen in occupational settings, the most common type of fatigue is low-frequency fatigue (LFF) (Westerblad et al., 2000). During low frequency fatigue, the force generating capacity of the muscle is reduced in response to muscle stimulation of 1-20 Hz, but the force generation response remains when stimulation is of a higher frequency (50 – 100 Hz) (Johnson et al., 2013). In the early onset of the LFF process, the muscle becomes potentiated and the effects of fatigue (primarily the decrease in force generating capacity) are minimized. As a result, there are increases in twitch forces and contraction times (Johnson et al., 2013). Eventually, after the twitches become maximally potentiated, the fatigue effects become too great to allow for maintenance of the force generating capacity. When the task is performed for a long enough time, eventually the force response is reduced, and the contraction time begins to slow. As this progresses, MVC force decreases as well. During the first cycle of our task, potentiation increased and peaked for all of the orders. After this point, twitch and MVC forces began to decrease, and exponential relaxation times began to increase. There were significant increases in MVC forces, as well as peak twitch forces, but all within the first cycle of the experimental protocol. The changes that occurred in the first cycle in MVC force are likely due to increased potentiation of the muscle during that point in time.

Peak twitch magnitudes, evoked by electrical stimulation, are significantly impacted by the conditioning contraction that immediately precedes them (Sale, 2004). Fukutani et al., (2012) examined the impact of a conditioning contraction on an isometric twitch, as well as maximum voluntary contraction. Participants were strapped into a device that measured plantar flexion torque, and an electrode was used to stimulate the posterior tibial nerve. Conditioning contraction (CC) intensities of 40, 60, 80 and 100% MVC were tested. Immediately following the CC (within 3 seconds), twitch force and MVC force were collected. They found that twitch intensities were significantly greater after the CC, as well greater with increasing CC intensity levels. MVC forces were not significantly different before and after the CC for the 40% and 60% CC, but the MVC force was higher after the CC in the 80 and 100% MVC CC conditions. In our study, the effect of plateau order was present most prominently during the first cycle. We found a significant difference between order 0-15-30-45 and order 45-30-15-0 during the 0% task plateau. This finding was likely because the 0% task plateau occurred first for the 0-15-30-45% MVC order, whereas it occurred last in the 45-30-15-0% MVC plateau. For the order beginning with the 45% MVC plateau, the twitch was already potentiated by a history of other conditioning plateaus, prior to reaching the point where the twitch occurred during the 0% task plateau. This effect of conditioning plateau was evident in our experiment, even though our conditioning plateaus were not as great in intensity as the Fukutani et al., (2012) experiment. If the plateaus used in our study would have been of greater intensity, it is possible that the interaction between order, plateau and cycle would have been even more prominent and, possibly, even statistically significant.

We observed a limited effect of the order of plateaus, within a cycle, on the overall accumulation of fatigue. However, we studied the flexor pollicis longus muscle, because this was a simple muscle system where the measured forces were predominantly the result of the contraction of one specific muscle. Fukutani et al., (2014) found that there was significantly greater potentiation from conditioning contractions of less than 60% MVC during thumb adduction, compared to plantar flexion. As the degree of potentiation appears to be significantly affected by the body part and joint that is being examined, it is not known how the results from our study would apply to other joints and/or muscles in the human body. Finally, participants in our study performed a fatiguing protocol for 12 minutes. In an industrial application, workers may perform up to 500 cycles in a day in an automotive assembly plant, meaning that any of the positive effects of potentiation are likely lost so early in the work day that they are not important to consider when analyzing a workstation.

4.5.0 CONCLUSIONS

We found that the order of force plateaus, within a cycle, had a small impact on the accumulation of fatigue during a task. Most of the effects involving order that were observed occurred in the first cycle. The effect of order of plateaus within a cycle throughout the remaining cycles was minimal and consistent in cycles 2 through 5. During the first cycle, of five, twitch potentiation appeared to have a significant influence in the amount of voluntary force generated. In our experimental protocol, the order that began with the highest force effort (45% MVC) produced a higher twitch during the very first plateau, compared to the order that began with the lowest force effort (0% MVC). Once the second cycle began, all twitches appeared to become maximally potentiated, and the order effect no longer appeared to play an important role. In agreement with the results found in a recent handgrip study with a complex MVC-relative profile (Sonne et al., 2014), our current study supports the hypothesis that potentiation is responsible for the increase in force generating capacity during the initial phase of a fatiguing protocol.

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CHAPTER 5:
A modified version of the three-compartment model to predict fatigue during submaximal tasks with complex force-time histories

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ABSTRACT

This three-compartment model (Xia & Frey Law, 2008) ($3CM_{XFL}$) has been validated for the prediction of endurance times for various joints in the human body, by simply modifying the fatigue and recovery rates in the model (Frey Law et al., 2012). However, it is not known how well the $3CM_{XFL}$ predicts fatigue levels during intermittent tasks, consisting of repeated efforts "on" to a single force level, then "off" to complete rest. In addition, most work tasks are more complex than on/off (Iridiastadi & Nussbaum, 2006), and it is not clear if the current $3CM_{XFL}$ can be used for the ergonomics analysis of the full range of occupational tasks. We collected 9 experimental conditions, across 5 different studies, consisting of repeated sequences of submaximal plateaus of either 12 or 15 seconds in length, varying between 0 and 45% of MVC, followed by rest. The 3CM was modified such that the fatigue rate was scaled to the current activation level and the recovery rate was scaled based on a gradient depending on both the current activation level and fatigue level (termed the graded motor unit 3CM, or $3CM_{GMU}$). The $3CM_{XFL}$ was also optimized (by modifying the F and R coefficients – referred to as $3CM_{OPT}$) to predict fatigue throughout the experimental trials.

We used the data from 7 conditions to determine the optimal fatigue and recovery rates for the $3CM_{GMU}$ and $3CM_{OPT}$, then tested the optimized model with data from the remaining 2 conditions. The $3CM_{GMU}$ resulted in an root-mean squared difference (RMSD) of 4.1 ± 0.5% MVC over the course of trials that had an average strength loss (ie. fatigue) of 31.0 ± 1.1% MVC. However, the $3CM_{GMU}$ model performed poorly for endurance tasks, predicting an asymptote at 29% MVC, compared to 6.1% MVC seen with the $3CM_{XFL}$. The $3CM_{OPT}$ also produced poor predictions of endurance times, with an asymptote predicted at 49% MVC. Mechanisms exist that significantly alter the amount of fatigue and recovery in static, endurance contractions compared to intermittent contractions. The $3CM_{GMU}$ model is a preferred method for evaluating submaximal force patterns consisting of intermittent efforts by the muscles of the hand and forearm. Future work should aim to develop a universal fatigue model that performs well for endurance, intermittent and complex task time-histories.

Keywords: Muscle Fatigue, Modelling, Ergonomics

5.1.0 INTRODUCTION

The integration of fatigue models, into existing ergonomics software, is essential for preventing chronic injuries in the workplace. There has been extensive research conducted on the inclusion of fatigue models into proactive tools for the purpose of ergonomic analysis with digital human models (DHM) (Brouillette et al., 2012; Honglun et al., 2007; Ma et al., 2008; Vignes, 2004). The end goal of this line of research is to allow for an accurate prediction of muscle fatigue during complex industrial tasks, thus proactively reducing the risk factors related to musculoskeletal injuries before the job exists in reality on the assembly line. Xia and Frey Law (2008) developed a simple, yet powerful, model for predicting muscle fatigue and recovery, which consisted of only three compartments comprised of: 1) motor units that are fully activated, 2) motor units at rest and 3) motor units that are completely fatigued. They proposed that an advanced muscle recruitment in their model may increase its accuracy. This hierarchy would allow for separate fatigue and recovery parameters to be set based on the composition of fast and slow twitch fibres within the muscle(s) of interest (Xia and Frey Law, 2008). However, such a hierarchy has not been used in further validation of the model. Currently, the model requires the input of separate coefficients that represent the fatigue (F) and recovery (R) rate of the system based on the known properties of the motor unit prior to the start of the prediction.

Initial validation of the model focused on finding single *F* and *R* coefficients that would accurately predict endurance times. Results from validation showed consistencies with other predicted endurance times (El ahrache et al., 2006), as well as useful predictions of remaining muscle strength and perceived exertion. Further, testing of the model has led to the determination of a separate set of F and R coefficients to accurately predict endurance times specific to different body parts (Frey Law, et al., 2012). Through initial testing of the model, endurance times were modelled with high accuracy for various body parts (Frey Law et al., 2012). In the initial development of the model, intermittent contractions and sinusoidal force patterns were also modelled, but predictions for these force patterns have not yet been validated (Xia and Frey Law, 2008). Without further validation using complex force histories, it is unknown how this model will perform in tasks more representative of industrial work.

The purpose of this study was to validate Xia & Frey Law's fatigue model with complex force patterns, and to provide a physiological basis for modifying fatigue and recovery rates to improve the biological fidelity of the model. Previous research identified the onset of fatigue occurring at lower levels of %MVC than the Xia and Frey Law model predicted using maximum endurance times (Hagberg, 1981; Sjøgaard et al., 1986). As stated by Xia and Frey Law (2008), motor units of different fiber composition fatigue at different rates, and motor unit recruitment depends on the state of fatigue, as well as the demands of the task. This study aims to increase the biological fidelity of the model by incorporating a spectrum of fatigue and recovery properties into the M_A, M_R and M_F compartments (Figure 5.1), to accurately reflect the recruitment, activation and recovery of motor units based on their physiological properties. It was expected that modifying fatigue and recovery rates, based on current activation and fatigue levels, will improve the fidelity of the model, specifically during tasks that feature more complex, varying force patterns.

5.2.0 METHODS

5.2.1 THREE-COMPARTMENT MODEL (3CM) OF MUSCLE FATIGUE

According to Xia & Frey Law (2008), the interaction between the three components of the fatigue model: 1) M_A – motor units that are fully active, 2) M_R – motor units at rest, and 3) M_F – motor units that are completely fatigued. The model is explained in Figure 5.1.

Coefficients *F* and *R* represent the rate of fatigue and recovery in the model, respectively, and can be modified to reflect specific motor unit types. The coefficient *C* represents the time varying muscle activation-deactivation drive. Based on the target load (*TL*) and the existing muscle fatigue parameters, the *C* variable is determined as a function of the muscle force development (L_D) factor and the muscle relaxation factor (L_R)(Figure 5.1 A) (Xia & Frey Law, 2008). These force development (L_D) and relaxation factors (L_R) were set to values of 10, as per Xia & Frey Law, (2008). The M_A compartment reflects the proportion of motor units fully active. The percentage of motor units, active at a given time, was assumed to be directly related to the muscle force being generated. For the purpose of application of this model, if using normalized target loads (ie., loads between 0 and 100% of maximum force generation), the M_A compartment reflected the demand. If M_A can no longer achieve the target demand, this is indicative of task failure.

Brain effort (BE) and residual capacity (RC) were also modelled by Xia and Frey Law (2008). Residual capacity (RC) was used to describe the remaining strength capacity of the muscle, where 0% indicates no strength reserve remaining, and 100% represents full, non-fatigued, strength. For example, if RC is equal to 0.9, only 90% of maximum strength could be achieved. Xia and Frey Law (2008) propose that the residual capacity can be decreased to reflect central fatigue, though this has not been tested yet. The RC represents the remaining force generating capacity, and can be reflect fatigue or, conversely, recovery during a task. Brain effort (BE) represents the central drive required to drive the muscle (Figure 5.1 B). This is influenced by the residual capacity and the target load (as seen in Figure 5.1, inset B). As a result, with a constant target load, brain effort would need to increase in response to fatigue.

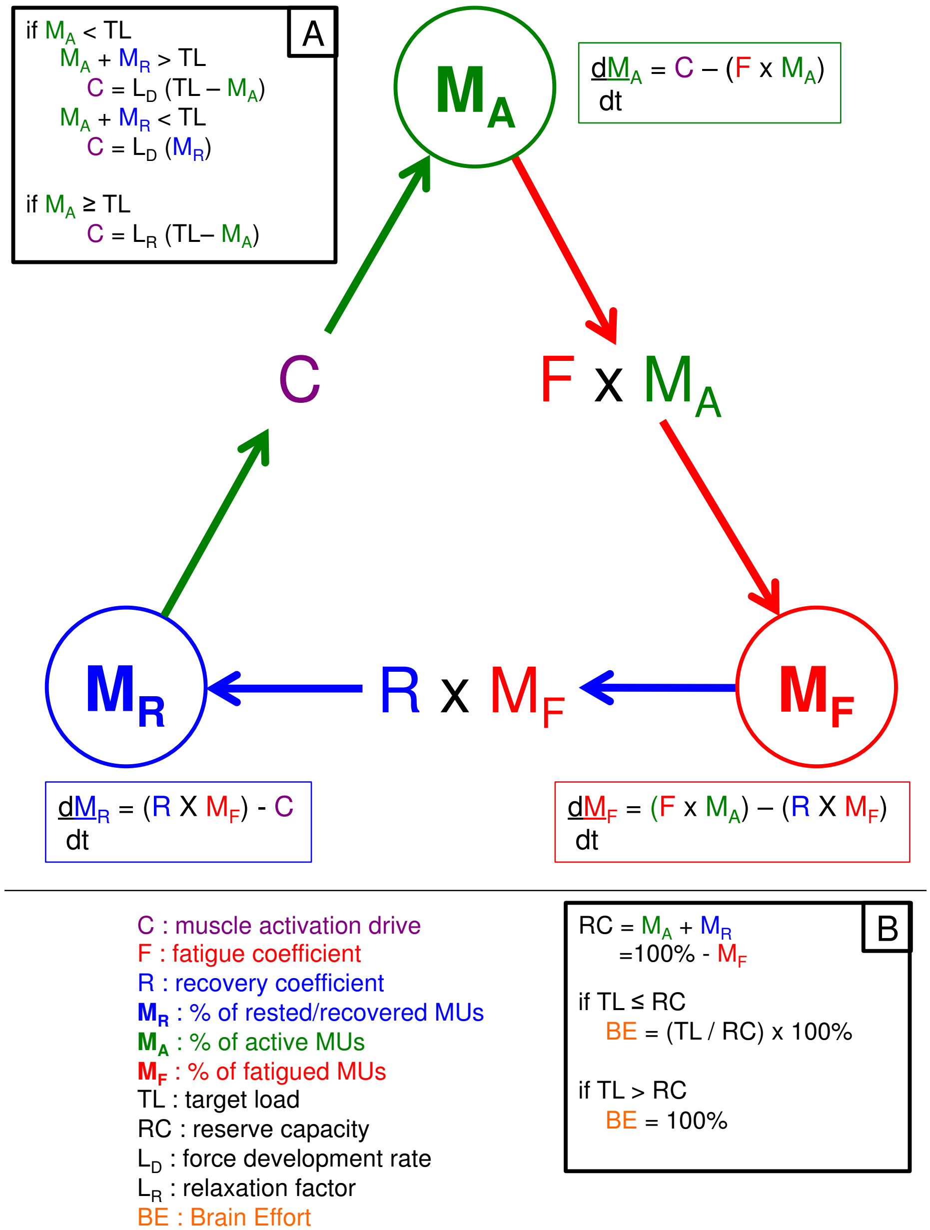


Figure 5.1. The relationship between compartments of M_R, M_A and M_F are controlled by the F and R coefficients, as well as the controller variable (C). The controller variable determines the rate in which motor units move from rested to active, and from active to fatigued, and is defined by the equations in inset A. One significant change, from the $3CM_{XFL}$ to our proposed version of the mode ($3CM_{GMU}$), is the substitution of BE for TL to drive the demand on the muscle (defined in inset B). This would reflect the increasing effort required from the muscle, given a constant force, when fatigued.

5.2.2 DEFINING MODEL FATIGUE AND RECOVERY CAPACITIES

As previously mentioned, fatigue and recovery rates of the M_A and M_F compartments, are represented by the *F* and *R* coefficients, respectively, in the 3CM. The relative fatigability of each of the motor units was scaled relative to the suggested *F* (0.0098) and *R* (0.00064) coefficients for hand/grip from Frey Law et al. (2012). Bigland-Ritchie et al. (1986) showed that there was an increase in motor unit recruitment as a factor of both muscle fatigue and activation level. This occurred to compensate for contractile failure during a submaximal static contraction. To simulate the impact of increasing activation on a muscle, at a set intensity level, we drove the model with the predicted brain effort as opposed to the target load. To improve the biological fidelity of the model, we modified the rate in which the model would fatigue as a factor of the level of activation (Figure 5.2). As seen in Fuglevand et al., (1993), there is a sigmoidal relationship between activation level and muscle force production. However, for simplicity, we modelled the increase in fatigue rate as a linear function, increasing with activation level. The magnitude of the 3CM *F* value (F(i)) was assumed to increase linearly with brain effort (Figure 5.2).

Fuglevand et al., (1993) developed a model of recruitment and rate coding organization in motor-unit pools. This model was used to simulate isometric muscle force, and simulated EMG, from a pool of 120 motor units. We used this model to determine the recruitment threshold of the final (ie. largest) motor unit being recruited. We assumed that, if all motor units were active, there would be no recovery.

Using the suggested Fuglevand et al., (1993), we assumed that the first unit is first recruited at an arbitrary activation level of 1. This unit began firing at a rate of 8 imp/s, increasing to a maximum rate of 35 imp/s. The final motor unit became active at an activation level of 30 arbitrary units, also beginning at 8 imp/s, and increasing to a level of 25 imp/s (assuming an increase in firing rate of 1 imp/s for every 1 unit increase in activation). Using equation 8 from Fuglevand et al., (1993), the last unit would increase to a maximum activation level of 30 + (25 – 8) = 47 imp/s. Given that the final unit became active at 30 activation units, and the maximum activation level was 47 units, the threshold for activation of the final motor unit was assumed to occur at 30/47, or 63.8% of maximum activation.

In an active muscle system, if all motor units are recruited and active, then no motor units can recover. Accordingly, the 3CM R-value (*R(i)*) was modified based on both the activation level (M_A), and the level of muscle fatigue (M_F) within the model. If the activation level of the model was above the threshold of the final motor unit activation (0.638), the *R* coefficient was set to 0. At sub-threshold levels, the recovery of the system was modified using the equation for *R(i)* in Figure 5.2. The values for *F(i)* and *R(i)* were substituted for variables *F* and *R* in the equations presented in Figure 5.1, inset A. These modifications of the fatigue and recovery capacities of the muscle will impact the performance of what will be referred to as the “graded motor unit” version of the 3CM ($3CM_{GMU}$).

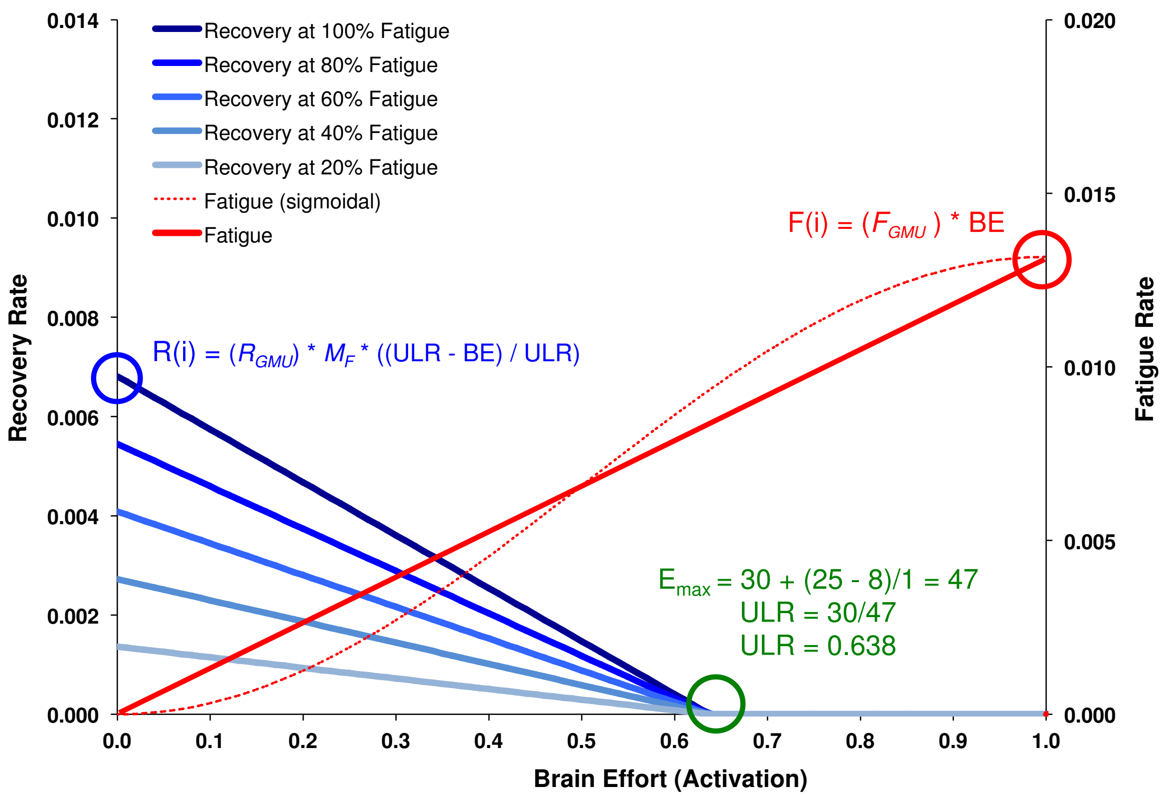


Figure 5.2. The *F* and *R* coefficients were modified based on the current activation rate and level of fatigue during the simulation. The F_{GMU} and R_{GMU} values were optimized, and then modified by the equations seen for F(i) and R(i). For example, at 45% of brain effort, the F(i) value would equal 0.0132 * 0.45 = 0.00882. For a fatigue level of M_F = 20%, and an activation level of BE = 30%, the R(i) value would equal (0.0068) * 0.2 *((0.638 – 0.45)/(0.638)) = 0.00037718. These values were then be substituted into the equations contained in Figure 5.1.

5.2.3 EXPERIMENTAL VALIDATION

A total of 5 studies (Dang, 2013; D'Isabella et al., 2013; Sonne et al., 2014; Sonne & Potvin, 2014; Whittaker, 2014), consisted of a total of 9 experimental conditions, and were used to examine the performance of both the original three-compartment model (3CM), the $3CM_{OPT}$ as well as the $3CM_{GMU}$ model. Studies by Dang, D'Isabella and Whittaker were completed as undergraduate thesis projects under the supervision of the authors of the current paper. The remaining two studies are included in this thesis in Chapters 3 and 4.Seven of these conditions were used to determine the optimal F and R coefficients for the $3CM_{GMU}$ and the $3CM_{OPT}$ model, as well as the fatigue predictions from the original $3CM_{XFL}$. The details of the optimization will be outlined in section 5.2.4. The remaining two conditions were used to perform an independent test of the predictions from the $3CM_{XFL}$, $3CM_{GMU}$, and $3CM_{OPT}$ models.

All participants, in all experimental conditions, were females from an undergraduate and graduate student population. All studies received ethical approval from the University's REB. Participant details are listed in Table 5.1.

In all cases, participants held isotonic target efforts (normalized to pre-trial MVC) for either 12 or 15 seconds (Figure 5.3). The sub-maximal force plateaus ranged between 0 and 45% of MVC, and were followed by a brief MVC lasting 2 or 3 seconds. This was followed by a 2 or 3 second rest period. The MVC following each plateau was compared to the pre-trial MVC, and the loss in force was recorded as the level of fatigue. The participants completed numerous cycles of the plateaus until the end conditions of each experiment were met (Table 5.1).

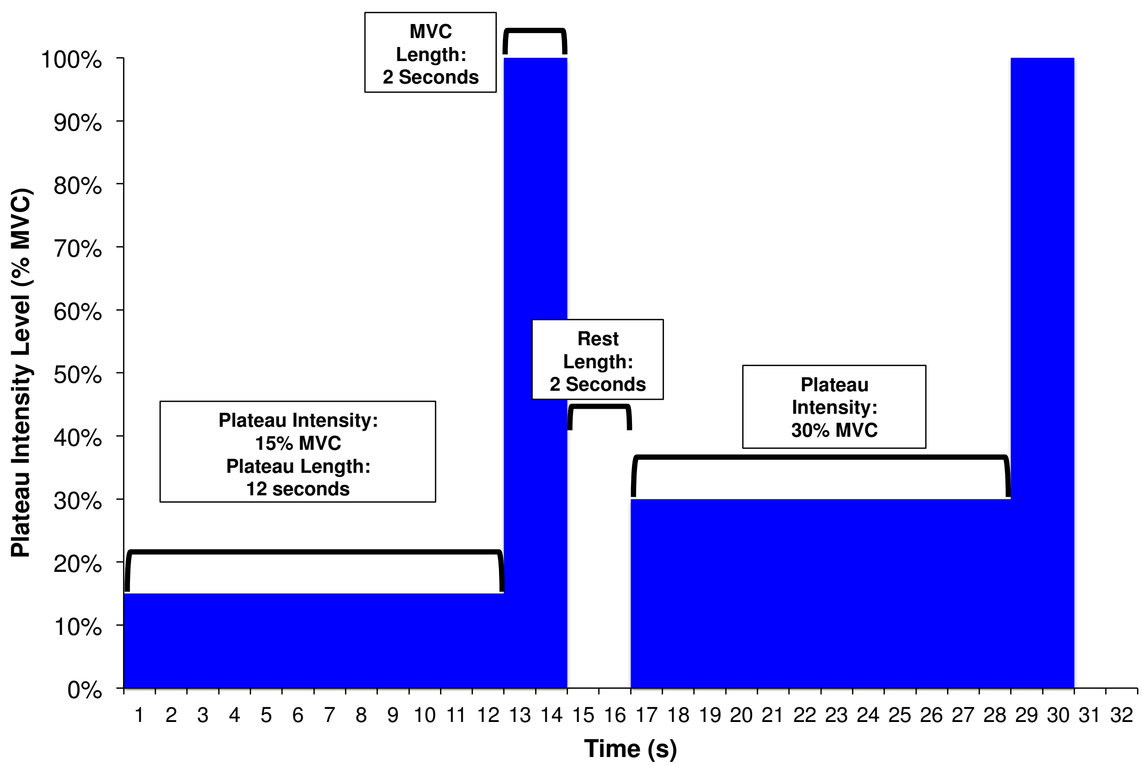


Figure 5.3. All experimental conditions consisted of an effort of submaximal intensity being held for either 12 or 15 seconds (12 seconds in this example), followed by a brief MVC and rest. Each MVC was paired with a rest break of matching duration (in this example, 2 seconds followed by 2 seconds).

Table 1. Participant demographics from the 5 studies used to optimize F and R coefficients. The information on each protocol is also outlined in the table. Details on plateau and MVC length can be found in Figure 5.3. The n in this table refers to the number of participants in each experimental condition.

	Optimization Conditons					**Testing**
	Sonne et al., (2014)	**Whittaker (2014)**	**Dang (2013)**	**D'Isabella et al., (2013)**	**Sonne & Potvin (2014)**	**Sonne & Potvin (2014)**
Effort Type	Hand Grip	Thumb Flexion	Thumb Flexion	Hand Grip	Thumb Flexion	Thumb Flexion
n	10	10 (x 2 Conditions)	10	10 (x 2 days)	17	16
Age	23.3 ± 3.7 yrs	21.3 ± 1.2 yrs	21.3 ± 1.1 yrs	21.1 ± 1.1 yrs	25.7 ± 2.8 yrs	24.1 ± 2.6 yrs
Height	1.65 ± 0.1 m	1.66 ± 0.1 m	167.8 ± 0.1 m	1.66 ± 0.04 m	1.66 ± 0.1 m	166.8 ± 0.1 m
Weight	63.4 ± 7.3 kg	56.9 ± 6.6 kg	66.4 ± 11.3	56.3 ± 5.4 kg	62.8 ± 11.8 kg	64.1 ± 11.6 kg
Plateau Order (% MVC)	0-15-30-45 -30-15	Front = 0-15-25-15 -30-15-35-15 & Even = 0-0-15-0 -25-0-15-0-30-0 -15-0-35-0-15-0	0-20-10-30-10	0-10-20-30-40 -30-10-20-40 -20-30-40-10 -40-10-20-30	0-10-15-10 -30-10-45-10 & 45-10-30-10 -15-10-0-10	15-10-45-10 -0-10-30-10 & 30-10-0-10 -45-10-15-10
Plateau Length	15 s	12 s	15 s	12 s	12 s	12 s
Duration of the MVC & the Rest segments	3 s	2 s	2 s	2 s	2 s rest, 2 s MVC, 2 s rest	2 s rest, 2 s MVC, 2 s rest
Cycle Duration (s)	126 s	256 s	95 s	272 s	144 s	144 s
Duty Cycle	0.74	0.39	0.74	0.83	0.69	0.69
Criteria for inclusion in model validation	Participants could not reach 65% of their MVC at the end of the third cycle	All participants were used	Participants could not reach 65% of their MVC at the end of the 4th cycle	Participants could not reach 65% of their MVC after 17 plateaus	All participants were used	All participants were used
Participants included in model validation	5	20	6	7	17	17
Cycles Tested	3	5	4	4	5	5
Determination of trial end	MVC < 65% of pre-trial max	5 Cycles	MVC < 65% of pre-trial max	MVC < 65% of pre-trial max	5 Cycles	5 Cycles
Notes		Front: Plateaus done sequentially in the first 128 s, then 128 s rest. Even: Each sequence of Plateau-MVC-Rest was followed by 16 s rest.		The reliability of the fatigue measures was tested over two days. However, there were no significant differences between the two days.	For all conditions in Sonne & Potvin (2014), stimulation of the flexor pollicis longus occurred during the first 2 second rest break prior to each MVC. Additionally, a 10% MVC "reference" plateau followed each task plateau.	

Two types of activities were used; either an isometric hand grip, or an isometric contraction of the distal aspect of the thumb (Figure 5.4). In all of the optimization conditions, participants completed a training day, where they practiced increasing from a given sub-maximal plateau level up to a brief MVC. Participants performed the experimental protocol during the ensuing collection sessions. In two of the five studies used to determine optimal F and R coefficients, participants had more than one testing condition, resulting in a total of 7 conditions in the optimization.

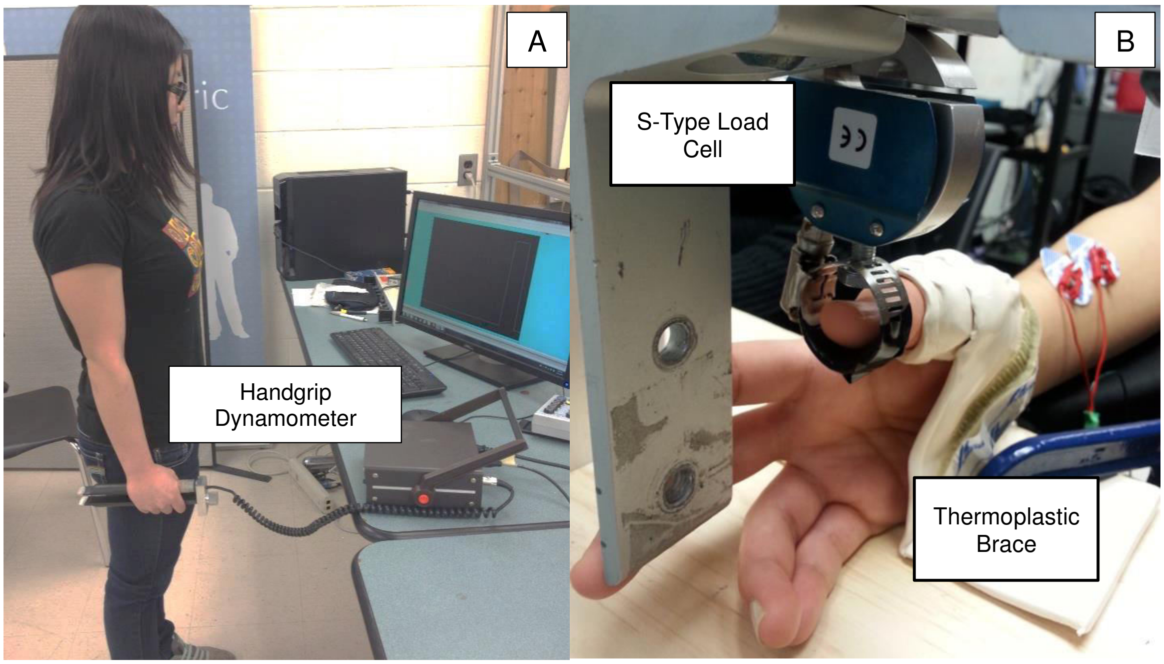


Figure 5.4. Participants performed either an isometric handgrip task using a handgrip dynamometer (Inset A) or a flexion of the distal aspect of the thumb (inset B). They were instructed to exert forces that would trace a line over top of a force profile on a computer screen at various submaximal levels, followed by performing an MVC. All force data were smoothed with a half second moving average, and the MVC calculated after each plateau was compared to a pre-trial MVC value to calculate the level of fatigue.

5.2.4 DATA ANALYSIS

The experimental fatigue level was calculated by subtracting the MVC value, recorded after each plateau, from the rested MVC value. For each of the conditions described in table 5.1, the modelled fatigue level was calculated as the decrease in M_A during the MVC with respect to the initial M_A condition (1 – M_A). When determining endurance time in the sustained, isotonic trials described in section 5.2.6, the instance where MA could no longer maintain the target load was defined as the endurance time.

5.2.5 OPTIMIZATION OF FATIGUE AND RECOVERY COEFFICIENTS

Inputs were created for the fatigue model, that would scale the *F* and *R* coefficients with respect to the recommended coefficients for the hand/grip from Frey Law et al. (2012). The F and R coefficients were optimized for the $3CM_{GMU}$ and the $3CM_{OPT}$.The optimization toolkit in MATLAB (Mathworks, Natick, MA) was used to minimize the average RMSD between the mean of experimental data and the model's predicted fatigue values, over the course of all the time-histories from the 7 optimization conditions. The pattern search function was used, with the maximum number of iterations set to 200. For optimization of the $3CM_{GMU}$ and $3CM_{OPT}$, the lower bound, upper bound and initial point for the *F* and *R* value were 0.01, 20 (multiplied by the values of 0.0098 for *F*, and 0.00064 for the *R*) and 1.0, respectively.

5.2.6 TEST CONDITIONS

Data from 2 separate conditions were used to evaluate the optimized *F* and *R* parameters, as well as F_{GMU} and R_{GMU}; and both were from Sonne & Potvin (2014) (Chapter 4). Participants completed 5 cycles of a thumb flexion protocol consisting of pairs of task plateaus that were either 0, 15, 30 or 45% of MVC, followed by a 10% reference plateau. Each plateau was 12 seconds in length, followed by a 2 second rest, a 2 second MVC, and 2 more seconds of rest. The order of plateaus from these 2 conditions was: 1) 15-10-45-10-0-10-30-10 (n = 8 participants), and 2) 30-10-0-10-45-10-15-10 (n = 9).

All participants from these 2 conditions were used to calculate the mean experimental fatigue level for each test condition. The mean experimental fatigue levels were then used to examine the performance of the $3CM_{XFL}$, as well as the optimized $3CM_{GMU}$ and $3CM_{OPT}$.

5.2.7 ENDURANCE TIMES

Frey Law et al., (2012) performed a validation of the $3CM_{XFL}$ by optimizing *F* and *R* parameters to fit endurance times determined from a meta analysis by Frey Law & Avin, (2010). We calculated the endurance times using the optimized coefficients from both the $3CM_{GMU}$ and $3CM_{OPT,}$ and compared them against the values from Frey Law & Avin, (2010). Intensity levels were tested between 0.1 and 1.0, in increments of 0.1.

5.2.8 STATISTICAL ANALYSIS

To determine the fit of the optimized models ($3CM_{OPT}$ and $3CMU_{GMU}$), as well as the original $3CM_{XFL}$, the RMSD was calculated between experimental and predicted levels of fatigue during the 7 conditions used for optimization and the two test conditions. The R^2 was calculated between the optimized models and the experimental data for the $3CM_{XFL}$, $3CM_{OPT}$ and $3CM_{GMU}$. Finally, the error between the final predicted fatigue level and the final experimental fatigue value was calculated. This was done for all 7 conditions used for optimization, as well as the 2 conditions used for testing.

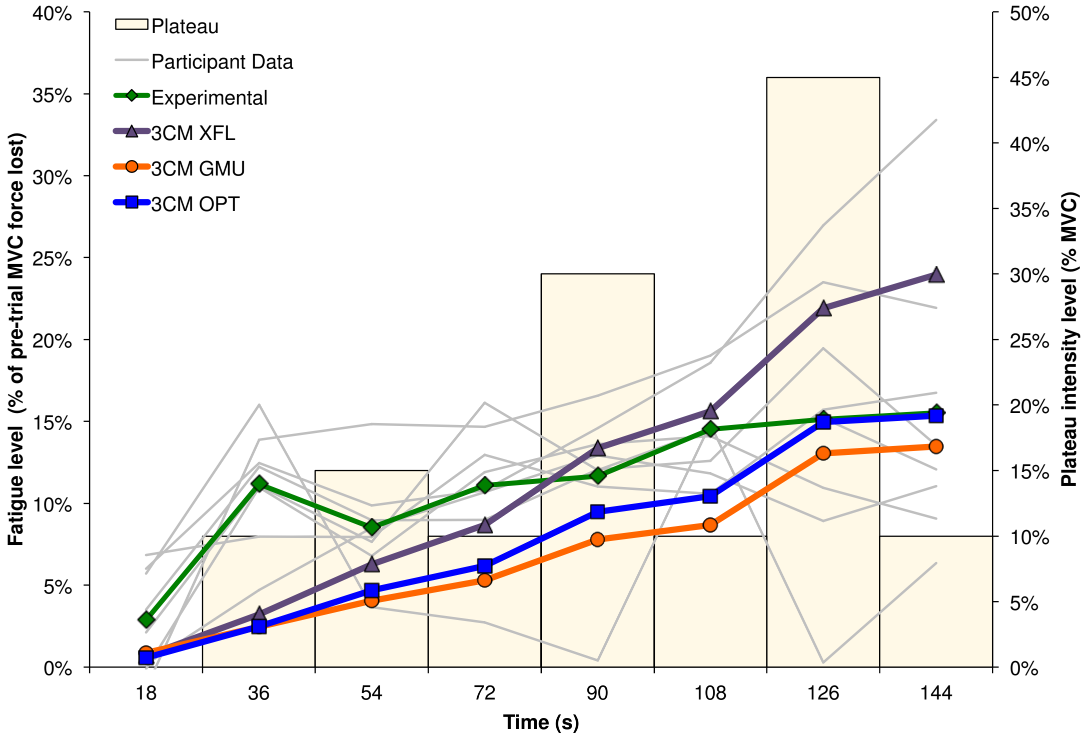


Figure 5.5. This is an example of experimental fatigue data as well as predicted fatigue data during one of the conditions used for optimization (shown from Sonne & Potvin, 2014; Order 0-15-30-45, with 10% MVC reference contractions after each task plateau). Each value is from the instance in time (x-axis) where the MVC occurred. The experimental values are calculated as the average of all participant data (n = 8 in this example). The predicted fatigue from the $3CM_{XFL}$, $3CM_{GMU}$, and the $3CM_{OPT}$ are also presented. The experimental level of fatigue (calculated as 1 – MVC after each plateau) was compared against the MA compartment during the MVC reported by each of the 3 models. The RMSD and R^2 values were calculated across the whole trial for each model. The final predicted fatigue value from each model was compared against the final experimental fatigue value, as well (at 144 s in this example).

A one-way ANOVA was used to determine significant differences between RMSD values calculated using the $3CM_{XFL}$, $3CM_{OPT}$ and $3CM_{GMU}$ for all 9 experimental conditions. Significant differences between each of the models were determined using Tukey's HSD post-hoc testing, with $p < 0.05$. Finally, the endurance times predicted with the $3CM_{GMU}$ were compared to those from Frey Law et al., (2012) with an RMSD calculation.

5.3.0 RESULTS

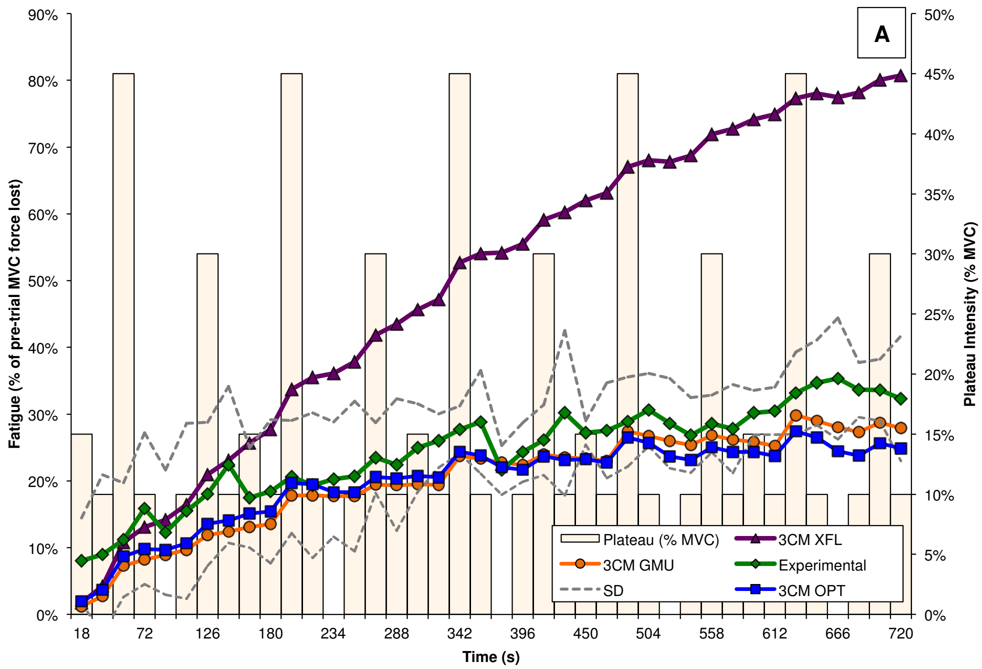
The mean RMSD, between experimental data and the $3CM_{GMU}$ then pooled across optimization conditions, was a 4.1% MVC, compared to 4.0% for $3CM_{OPT}$ and 29.4% MVC for $3CM_{XFL}$ (using its recommended hand/grip *F* and *R* coefficients). The R^2 between the experimental data and modelled data was 0.833 for $3CM_{GMU,}$ 0.824 for $3CM_{OPT}$ and 0.786 for the $3CM_{XFL}$. From the optimization conditions, the $3CM_{XFL}$ tended to overestimate the final fatigue level by an average of 45.6% MVC, while the average errors were -0.9% and -1.4% MVC with the $3CM_{GMU}$ and $3CM_{OPT}$, respectively. The statistics for each of the optimization conditions can be found in Table 5.2.

For the two test conditions, the original $3CM_{XFL}$ produced an average RMSD of 31.0% MVC compared to 4.4% with the $3CM_{GMU}$, and 4.5% MVC with the $3CM_{OPT}$. The R^2 between the experimental data and modelled data was 0.849 for $3CM_{GMU,}$ 0.815 for $3CM_{OPT}$ and 0.848 for the $3CM_{XFL}$. The mean RMSD, pooled across all 9 conditions, for the 3CM (29.7% MVC) was significantly higher than the RMSD calculated by both the $3CM_{OPT}$ (4.2% MVC) and $3CM_{GMU}$ (4.1)($p < 0.05$). There were no significant differences in RMSD between the $3CM_{OPT}$ and $3CM_{GMU}$.

Table 5.2. The RMSD, Final Fatigue Error and R^2 between the experimental and modelled data is presented for the three versions of the 3CM. Values are averaged across the 7 Optimization conditions as well as the 2 Test conditions. The n refers to the total number of plateaus in the experimental condition.

			RMSD			Final Fatigue Error			R^2		
	Condition	**n**	XFL	GMU	OPT	XFL	GMU	OPT	XFL	GMU	OPT
Optimization	Sonne, Hodder, Wells & Potvin (2014)	18	24.2%	5.2%	5.9%	38.9%	7.4%	2.2%	83.7%	88.8%	83.8%
	D'Isabella (2013)	17	11.8%	7.2%	4.7%	23.5%	-6.1%	-3.4%	91.4%	94.0%	96.0%
	Dang (2013)	20	18.9%	2.2%	2.5%	29.5%	-5.9%	-2.3%	95.9%	94.0%	92.4%
	Whittaker (2014) - Front Loaded	40	42.1%	3.2%	4.1%	56.9%	-3.3%	-1.8%	69.4%	73.0%	65.5%
	Whittaker (2014) - Even Loaded	40	41.5%	3.1%	3.4%	58.6%	-4.6%	-4.0%	81.3%	61.1%	50.0%
	Sonne & Potvin (2014) - 0-15-30-45%	40	33.5%	2.9%	2.4%	54.8%	4.6%	0.8%	86.4%	91.7%	91.2%
	Sonne & Potvin (2014) - 45-30-15-0%	40	33.6%	4.9%	4.7%	57.0%	1.9%	-0.9%	74.7%	74.1%	71.3%
	Mean	**215**	**29.4%**	**4.1%**	**4.0%**	**45.6%**	**-0.9%**	**-1.4%**	**83.3%**	**82.4%**	**78.6%**
Test	Sonne & Potvin (2014) -15-45-0-30%	40	30.3%	4.8%	5.1%	48.4%	-4.4%	-7.4%	91.8%	92.0%	87.6%
	Sonne & Potvin (2014) - 30-0-45-15%	40	31.8%	4.1%	3.9%	51.5%	-1.5%	-4.6%	88.4%	95.5%	95.5%
	Mean	**80**	**31.0%**	**4.4%**	**4.5%**	**49.9%**	**-2.9%**	**-6.0%**	**90.1%**	**93.7%**	**91.6%**
Total Mean		**295**	**29.7%**	**4.2%**	**4.1%**	**46.6%**	**-1.3%**	**-2.4%**	**84.8%**	**84.9%**	**81.5%**

Compared to the original three-compartment model ($3CM_{XFL}$), the *F* coefficient for $3CM_{OPT}$ was 82.0% of the original *F* coefficient and the recovery coefficient (*R*), 1046.1% of the original *R* coefficient for the $3CM_{opt}$. The F_{GMU} and R_{GMU} values, found to best predict fatigue in our experimental tasks, were 0.01316 and 0.00681, respectively.



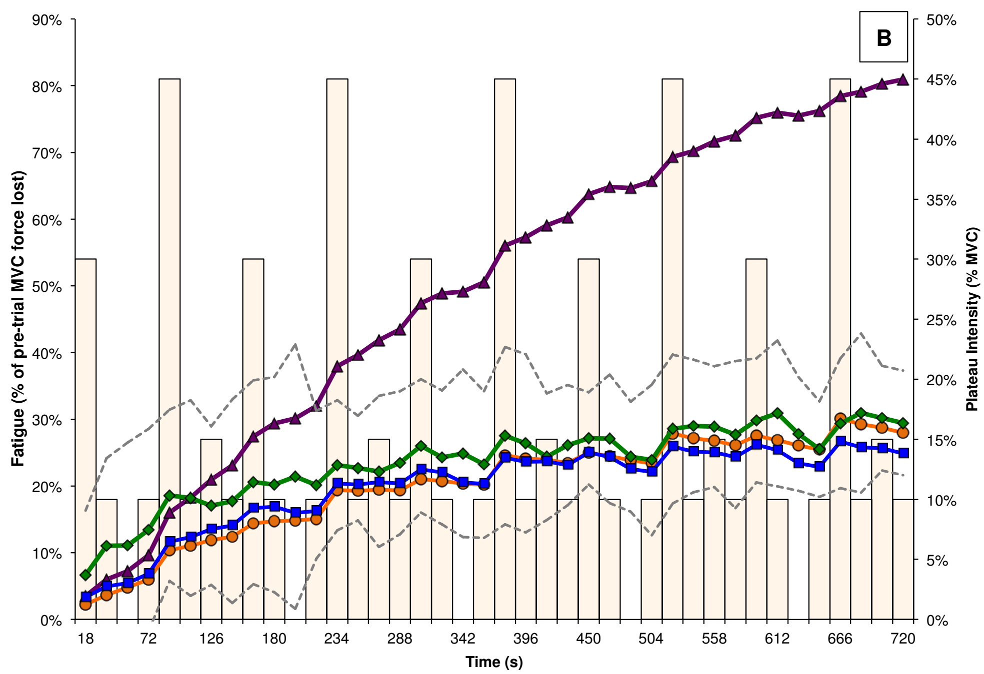


Figure 5.6. The mean experimental fatigue data (± SD) are plotted with the fatigue predicted with the $3CM_{GMU}$, $3CM_{OPT}$ and $3CM_{XFL}$ for the two test conditions: A) order 15-45-0-30 (n = 8), B) order 30-0-45-15 (n = 9). In the first cycle for both test conditions, both the $3CM_{XFL}$, $3CM_{OPT}$ and $3CM_{GMU}$ models predict fatigue values that are relatively similar to the experimental data, with the $3CM_{XFL}$ rising to more comparable levels of fatigue than the $3CM_{GMU}$. However, throughout the remainder of the fatiguing trial, the $3CM_{GMU}$ and $3CM_{OPT}$ follow the experimental data much more closely than the $3CM_{XFL}$. By the end of the trial, the $3CM_{XFL}$ is over predicting levels of fatigue by 48.4 to 51.5% of force lost.

The $3CM_{XFL}$ produced an asymptote (where the model would no longer fail during a static hold) at 6.13% MVC. Conversely, the $3CM_{GMU}$ predicted an asymptote and 29% MVC, compared to the $3CM_{OPT}$ which predicted an asymptote at 45.4% MVC. At levels of 30% MVC and higher, the RMSD between the $3CM_{GMU}$ and experimental data was 205.9 seconds, compared to 23.0 seconds for the $3CM_{XFL}$. The RMSD between experimental data and modelled endurance times for MVCs greater than 50% was 24.5 seconds, 20.6 seconds, and 47.3 seconds, for the $3CM_{GMU}$, $3CM_{XFL}$ and $3CM_{OPT}$, respectively (Figure 5.7).

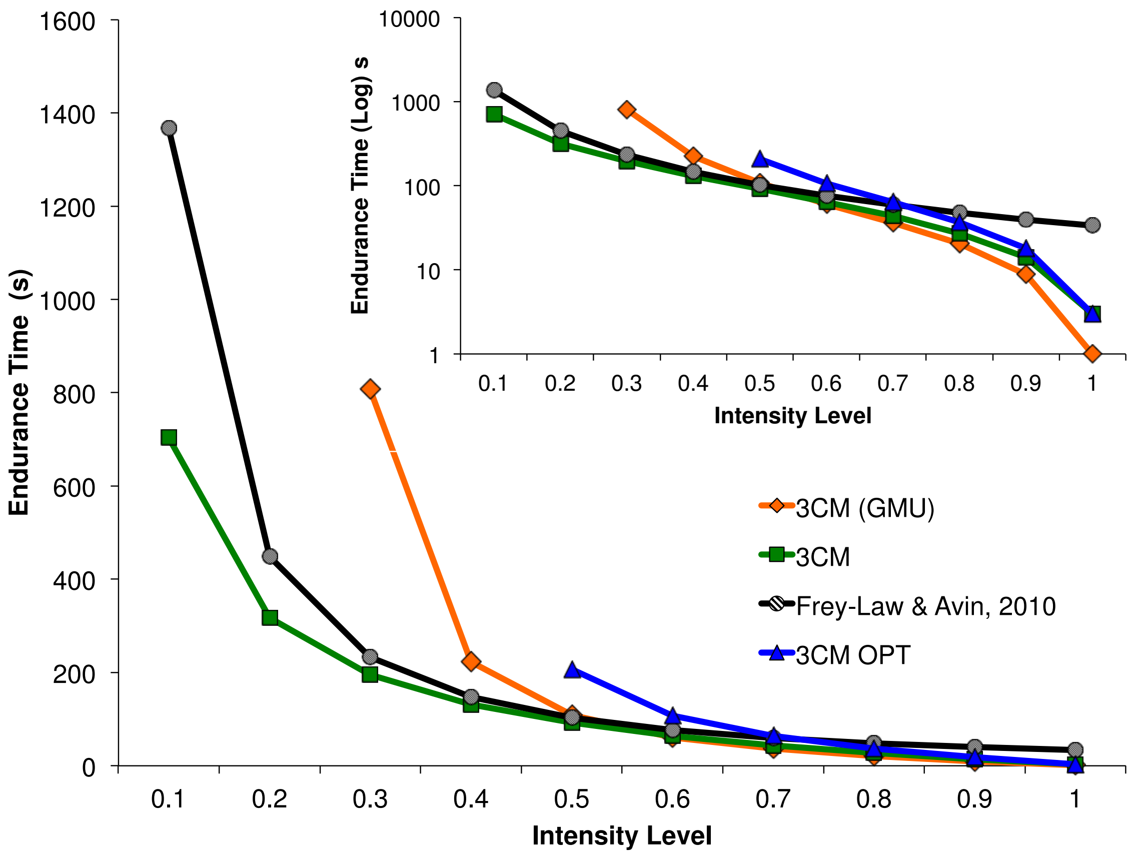


Figure 5.7. The endurance times predicted with the $3CM_{XFL}$, $3CM_{OPT}$ and the $3CM_{GMU}$ are plotted against the endurance times predicted by the Handgrip Model of Frey Law & Avin, (2010) at intensity levels of 0.1 to 1.0. The endurance times, plotted as a logarithmic function on the y-axis, are in the inset. The $3CM_{XFL}$ and $3CM_{GMU}$ are relatively similar between intensity levels of 1.0 and 0.4, however, they begin to significantly deviate at 0.3, before the $3CM_{GMU}$ reaches an asymptote at 29% of MVC (compared to an asymptote of 6.13% for the $3CM_{XFL}$).

5.4.0 DISCUSSION

Previously, models have been used in ergonomics for determining acceptable work to rest ratios, and accumulated fatigue levels. These methods were based, primarily, on studies featuring sustained isotonic contractions, or intermittent contractions at the same force level followed by complete rest. However, these types of simple contraction patterns are not reflective of industrial work and, as a result, these ergonomic tools may not have provided accurate predictions of fatigue. In proactive ergonomics, it is essential that methods be able to accurately predict risk factors for musculoskeletal disorders to reduce the likelihood of their occurrence on an assembly line. The 3CM is a simple method to predict fatigue levels given a wide array of force demand patterns associate with work. However, to date, the F and R coefficients had only been determined for endurance tasks. Our study aimed to validate the 3CM during complex force patterns, but also added in a physiological basis for modifying the fatigue and recovery parameters to properly predict fatigue.

The $3CM_{GMU}$ and $3CM_{OPT}$ provided a better prediction of muscle fatigue (average RMSD of 4.4% and 4.5% MVC, respectively) for our two test conditions, compared to the $3CM_{XFL}$ (RMSD = 31.0% MVC) The error between experimental and modelled data, in the prediction of the final fatigue level, was slightly lower in the $3CM_{GMU}$ than the $3CM_{OPT}$, but both optimized models produced much lower final error values than the $3CM_{XFL}$. Both the $3CM_{GMU}$ and $3CM_{OPT}$ are better predictors of fatigue than the $3CM_{XFL}$ during submaximal complex force patterns using muscles of the hand or forearm.

Frey Law et al. (2012) determined the optimal coefficients for their 3CM by: 1) performing a meta-analysis of endurance time data, then 2) finding the combination of *F* and *R* coefficients that minimized the error between predicted and experimental endurance times. The $3CM_{XFL}$ predicted an asymptote of 6.13% MVC (Frey Law et al., 2012); which means that it would be assumed that efforts of less than this intensity could be held indefinitely. Conversely, with the optimal coefficients determined with the 7 complex force pattern conditions, the $3CM_{GMU}$ predicts an asymptote at 29% of MVC for sustained isotonic trials. The method of Rohmert (1973) assumes indefinite hold times for efforts less than 15% MVC but others have challenged the physiological accuracy of this assumption (Frey Law & Avin, 2010; Frey Law et al., 2012; Potvin, 2012; Sonne & Potvin, 2014). Recommending a 29% MVC hold is nearly double that value, and surely not an accurate reflection of the physical capacity of human muscle during sustained contractions. This over-prediction indicates that it may not be possible to account for physiological differences, between intermittent and sustained contractions, with the simplified structure of the 3CM, even if more biological fidelity is incorporated, as with the $3CM_{GMU}$. While the endurance times predicted using the $3CM_{GMU}$ do not accurately reflect the experimental endurance times from Frey Law & Avin (2010), they are an improvement over the times predicted by the $3CM_{OPT}$. However, with both the $3CM_{OPT}$ and $3CM_{GMU,}$ there are significant errors in predicted endurance times for contraction intensities less than 50% MVC. The three variations of the 3CM model presented, in this these, should only be used for tasks similar to those with which they were optimized.

Tasks that have complete intermittent rest lead to increased blood flow (Vedsted et al., 2006), leading to a rhythmic emptying of veins which, in turns, allows reperfusion of the muscle (Zhang et al., 2004). Thus, periods of complete rest, which follow an effort, would cause a removal of metabolites, leading to increased endurance time. This mechanism was not directly modelled within the original 3CM. However, the large increase in R coefficients in the $3CM_{OPT}$ illustrates that there was substantially greater recovery rate in the intermittent contractions from our experimental trials. This may explain the over-prediction of the fatigue levels by the $3CM_{XFL}$ when compared to our experimental data, as well as the $3CM_{OPT}$ and the $3CM_{GMU}$ model.

Looft (2012) examine the applicability of the 3CM to intermittent tasks. He found that there was substantial error between predicted endurance times in isometric holds, compared to intermittent contractions for handgrip tasks. The predicted fatigue levels, during intermittent tasks of varying duty cycles and intensity levels, were compared every 30 seconds over the course of a 120-second simulated trial. The RMS difference was calculated between predicted and empirical fatigue levels at duty cycles between 0 and 100% and effort intensities between 0 and 100%. The RMS difference, between predicted and experimental force declines, gradually increased over the course of the trial, from 92.7% MVC at 30 seconds, to 238.0% MVC at 120 seconds. The increase in error over time is comparable to what was found between the $3CM_{XFL}$ and our experimental data (Figure 5.6).

Looft (2012) hypothesized that this lack of fit, between predicted and experimental fatigue levels for intermittent contractions of the hand/grip task, was due to a lack of experimental data at high duty cycles, which did not allow for optimization of F and R coefficients through a wide enough range of duty cycles. However, our study features 9 task conditions having duty cycles ranging between 0.39 and 0.83. Even with validation at these higher duty cycles, there was distinct deviation between the 3CM's predicted levels of fatigue and experimental data.

Gandevia, (2001) defines central fatigue as "a progressive reduction in voluntary activation of muscles during exercise", and peripheral fatigue as "fatigue produced by changes at or distal to the neuromuscular junction". Fatigue, occurring at a supraspinal, level results from a decreased output from the motor cortex, and may be due to factors such as motivation, pain, or other inhibiting factors (Gandevia, 2001). In all of these examples, there would be inhibited muscle activity, and force output would be significantly reduced. Since fatigue was quantified as a drop in maximum voluntary contraction force, this may have been a contributing factor that is not modelled in the 3CM, as we have currently only looked at peripheral factors related to fatigue.

In the validation of the $3CM_{GMU}$, errors were always highest during the first cycle of the task. In the test conditions, the mean RMSD for the first cycle was 3.5% MVC for the $3CM_{XFL}$, versus 6.5% MVC for the $3CM_{GMU}$, and 5.4% MVC for $3CM_{OPT}$. However, in the 5^{th} and final cycle of the task, the mean RMSD was

46.6% MVC for the $3CM_{XFL}$, compared to 3.7% MVC for the $3CM_{GMU}$, and 6.2% MVC $3CM_{opt}$ (Figure 5.6). This early, rapid increase in fatigue appears to be most likely due to the central mechanisms outlined above. Future research should examine the impact of central fatigue on force production during these types of complex force patterns, and create a correction factor for the $3CM_{GMU}$ to possibly elevate fatigue levels during the early onset of a task. The primary limitation of the $3CM_{XFL}$, $3CM_{OPT}$ and the $3CM_{GMU}$ is the inherent difficulty in accurately predicting endurance times for both sustained, isotonic and repeated, complex, intermittent force patterns using the same set of F and R coefficients. This somewhat limits the applicability of the current model for predicting fatigue during all industrial tasks. However, occupational muscle contractions are more frequently characterized by pauses and short breaks throughout the course of the work cycle (Iridiastadi and Nussbaum, 2006). Hence, the $3CM_{GMU}$ may still be applied to the evaluation of occupational tasks to represent an accurate level of muscle fatigue for tasks involving the hand or gripping.

Frey Law et al., (2012) found that the joint being examined had a significant effect on the accumulation of fatigue and endurance times. As a result, they proposed different *F* and *R* coefficients to fit the endurance times for the ankle, knee, trunk, shoulder, elbow, hand/grip and a general body set of coefficients. Theoretically, the starting *F* and *R* coefficients from Table 1 in Frey Law et al., (2012) could be modified using the corrections provided from the optimization of the $3CM_{GMU}$ model. As the motor unit composition of muscles can widely vary throughout the human body and, subsequently, the fatigability of different joints can be significantly impacted (Bellemare et al., 1983; Frey Law et al., 2012). Further research is required to adapt the $3CM_{GMU}$ to other joints. The $3CM_{GMU}$ and $3CM_{opt}$ should currently only be applied to intermittent contraction patterns involving handgrip, or contraction of the FPL. Also, the $3CM_{XFL}$ should only be applied to sustained, isotonic contractions.

5.0 CONCLUSION

The $3CM_{GMU}$ model builds on the theoretical basis of the three-compartment model of Xia and Frey Law (2008), and aims to improve its physiological fidelity. Optimizing the F and R coefficients, for both the $3CM_{GMU}$ and $3CM_{OPT}$, results in strong predictions of fatigue levels during complex, submaximal force patterns. By scaling the fatigability of motor units, based on their activation level and level of existing fatigue, we were able to predict muscle fatigue levels within approximately 4.1% MVC. The modifications made to the original 3CM allowed the $3CM_{GMU}$ to provide accurate predictions of fatigue accumulation and recovery during complex, intermittent force patterns. However, additional research should aim to: 1) apply the findings of this model to other body parts, and 2) improve the model to allow for accurate fatigue predictions during sustained isotonic, intermittent and complex contraction patterns.

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CHAPTER 6: THESIS SUMMARY AND DISCUSSION

6.1.0 THESIS SUMMARY

Muscle fatigue is an exercise-induced reduction in force generating capacity, resulting in performance detriments. Fatigue has been associated with discomfort, pain and risk of injury in the workplace (Chaffin et al., 2006). In ergonomics, the Rohmert rest allowance equation (Rohmert, 1973) has been commonly used to determine if acceptable rest is given to a worker, based on the normalized demands on the body, and the time to complete the task. A primary limitation of the Rohmert Rest Allowance equation is the assumption that tasks of 15% MVC or lower can be held indefinitely. This 15% level has been repeatedly shown to be false, as fatigue onset has been shown to occur during efforts as low as 2.6% of MVC (Hagberg, 1981).

The global purpose of this thesis was to evaluate ergonomic tools that assess repetitive work; to enhance understanding of muscle fatigue during complex force patterns, and to validate and improve on existing methods for determining fatigue accumulation. In Chapter 2, I aimed to validate the MAE equation (Potvin, 2012) for evaluating repetitive work with high duty cycles. The equation was developed using data from 69 different psychophysical conditions. However, only 4 of those conditions were from trials with duty cycles of greater than 0.5. In this thesis, we examined psychophysically determined MAEs for duty cycles of 0.5, 0.7 and 0.9, with frequencies of 2 and 6 per minute. This added 6 psychophysical conditions to support the MAE equation, and increased the number of conditions at DC > 0.5 from 4 to 10.

Current ergonomics tools, for evaluating repetitive work, have been validated using research consisting of sustained isometric forces (Frey Law and Avin, 2010; Rohmert, 1973), or intermittent on/off force patterns consisting of the efforts of the same intensity (Hagberg, 1981; Potvin, 2012; Yung et al., 2012). The primary focus of Chapters 3 and 4, was to examine how fatigue accumulates during more complex patterns. The patterns that I chose to examine were relative to the participant's pre-trial MVC, thus the patterns of forces performed by each participant were referred to as "MVC-relative" force patterns. In Chapter 3, I had participants perform a repetitive handgrip task in cycles that consisted of a "pyramid" of ascending effort levels, followed by descending effort levels. All participants completed the same profile, and the fatigue level was defined as a decline in maximum voluntary force. In Chapter 4, I more closely examined the effect of MVC-relative time-history, on muscle fatigue, by having participants perform a repetitive thumb flexion task consisting of four different force profiles. With each force profile, the participants performed 12 second long isometric contractions, consisting of "task" MVC-relative forces of 0, 15, 30 or 45% MVC. Each of these plateaus was followed by a 12 second long 10% MVC "reference" plateau. In addition to quantifying how force declined during each of these unique for profiles, I also examined the potential role of post-activation potentiation (PAP) in fatigue accumulation and recovery. PAP can lead to increased force generating capacity after a series of conditioning efforts (Sale, 2004) and can, potentially, mask the onset of fatigue during the initial phases of a task. Post-activation potentiation was examined by delivering an electrical stimulation to the flexor pollicis longus (FPL), and measuring the twitch force at the distal aspect of the thumb. In Chapters 3 and 4, characteristics of muscle fatigue were examined using electromyography and voluntary force level.

The three-compartment model ($3CM_{XFL}$) of muscle fatigue was originally developed by Xia and Frey Law, (2008). This model was validated, for sustained isotonic efforts, by optimizing its fatigue and recovery rates, and comparing the model's predicted endurance times against experimentally determined endurance times. As noted by Iridiastadi and Nussbaum, (2006), industrial work generally consists of a series of tasks followed by breaks and pauses. While the $3CM_{XFL}$ shows promise as a tool for evaluating fatigue levels, it has not been validated for evaluating industrial work. I ventured to increase the biological fidelity of the model by modifying the fatigue and recovery rates based on the brain effort and fatigue level at a given instance in time (a model referred to as the $3CM_{GMU}$). Additionally, I validated the model using the 5 experimental conditions tested in Chapters 3 and 4, as well as 4 other experimental fatigue data sets collected under my supervision. I also optimized the fatigue and recovery coefficients in the 3CM to best predict the fatigue during these more complex experimental conditions (referred to as $3CM_{OPT}$). Finally, the original 3CM was also used to predict fatigue during all 9 experimental conditions ($3CM_{XFL}$). The fit of the predicted model with the experimental data were calculated using the RMSD and cross-correlation. The difference between the final predicted fatigue level, and final experimental fatigue level, was also calculated.

In summary, I evaluated both the MAE equation (Potvin, 2012) and the 3CM (Xia & Frey Law, 2008) as tools for assessing repetitive work. First, I tested the high duty cycle portion of the MAE equation to ensure that the tool was validly determining MAEs at DCs ≥ 0.5. I addressed the inherent limitation of using sustained or intermittent isotonic contractions to validate fatigue models by examining fatigue accumulation during complex MVC-relative patterns. I increased the biological fidelity of the 3CM by modifying fatigue and recovery rates based on activation and fatigue levels. Finally, I then validated the modified 3CM using the fatigue patterns elicited by the complex MVC-relative patterns, as well as four other complex patterns. This thesis aimed to provide tools that can be used by ergonomists to assess repetitive work, as well provide insight into the fatigue process during industrially relevant work (Figure 6.1).

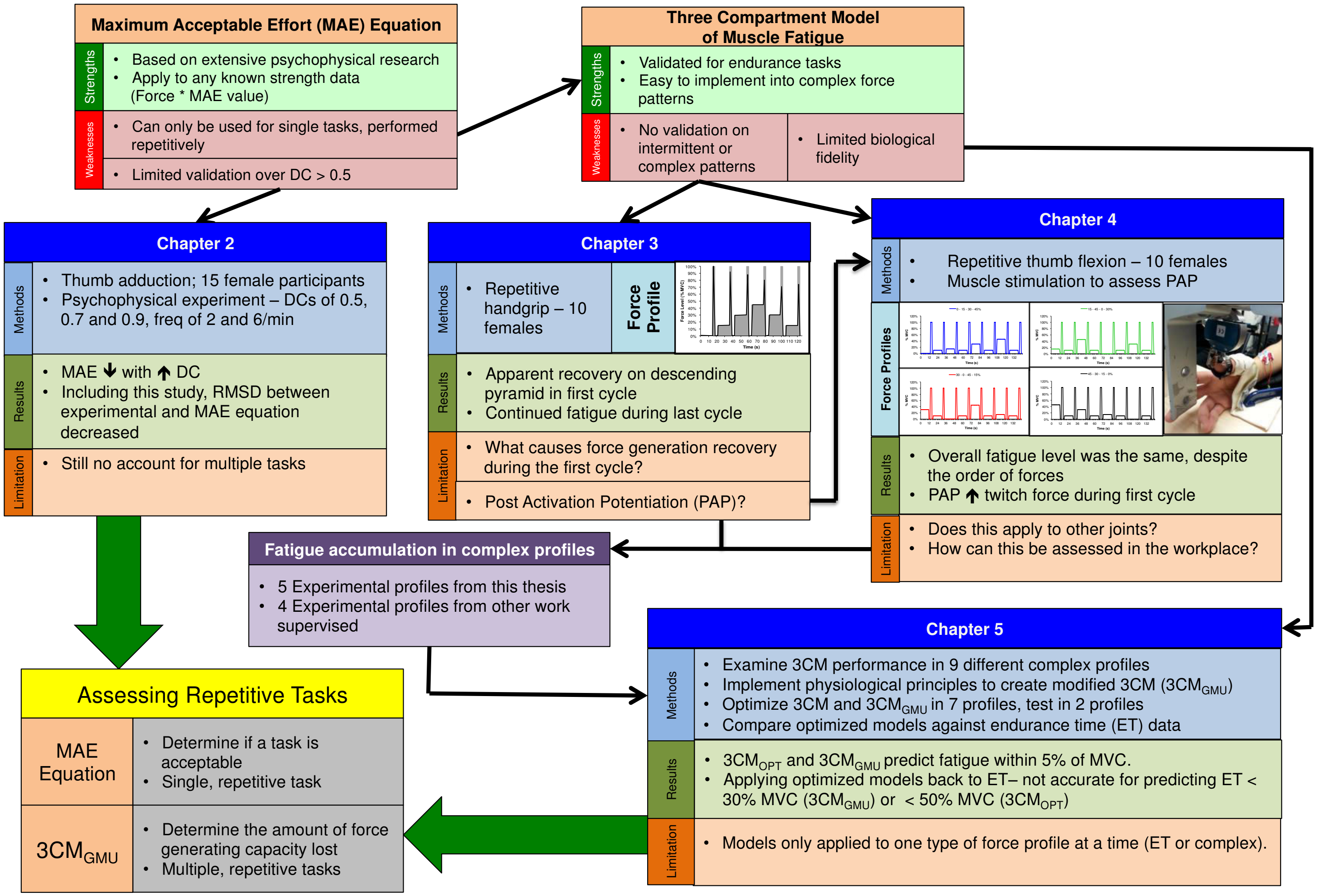

Figure 6.1. The MAE equation (Potvin, 2012) and 3CM (Xia & Frey Law, 2008) were tested with a series of three experiments. A final experiment increased the biological fidelity of the 3CM to better predict muscle fatigue during complex, MVC-relative force patterns. The overall goal of this thesis was to provide two validated tools for ergonomists, which can be used to assess fatigue during repetitive tasks.

6.2.0 MAJOR RESEARCH CONTRIBUTIONS

6.2.1 MAES FOR DUTY CYCLES GREATER THAN 0.5 AND THE MAE EQUATION

In Chapter 2, I determined maximum acceptable efforts during a thumb abduction task, for duty cycles of 0.5, 0.7 and 0.9. For each duty cycle condition, frequencies of 2 and 6 per minute were also tested. The MAEs significantly decreased between DCs of 0.5 and 0.9, and were significantly lower for a frequency of 6/minute, compared to a frequency of 2/minute. The MAE equation (Potvin, 2012) was originally only validated with only 4 conditions that had DCs greater than 0.5. In the initial testing of the equation, there was an RMSD between the predicted and experimental values (n = 69) of 7.23% MVC. Including the 6 values from this study (n = 75) actually lowered the RMSD to 7.05% MVC. Compared to the MAE equation's predicted MAE values, the MAEs calculated in this study were lower than those predicted with the MAE equation for DCs of 0.5 and 0.7, but higher at a DC of 0.9. The data from this study lend support to the validity the MAE equation for tasks up to at least DC = 0.70, though the data over estimate MAEs for DCs closer to 0.9, according to physiological data.

6.2.2 FATIGUE DURING MVC-RELATIVE PATTERNS

Chapters 3 and 4 examined the accumulation of fatigue during MVC-relative patterns. Chapter 3 examined one specific MVC-relative force pattern using a repetitive handgrip task, where as Chapter 4 examined four separate MVC-relative patterns using a repetitive thumb flexion task. For all of these patterns, participants held an effort relative to their rested MVC for a plateau of 12 to 15 seconds, and then performed a maximum voluntary contraction for 2 to 3 seconds. Fatigue was measured as a decline in voluntary force capacity after each plateau.

6.2.3 FINDINGS FROM REPETITIVE HAND GRIP

The fatigue level increased as participants performed an ascending series of MVC-relative plateaus (moving from 0% to 15%, 30% and 45% MVC). During the first cycle of the repetitive task, participants did not continue to accumulate fatigue as they performed the descending series of plateaus. Compared to the fatigue level after the 45% plateau, participants maintained their MVC force following a 30% MVC plateau, and increased their MVC force following a plateau of 15% MVC. In the final cycle of the repetitive handgrip task, there was no evidence of fatigue recovery at any point of time during the force profile. The unique pattern of fatigue, observed during the first cycle, may be due to post-activation potentiation, greater fatigue of slower motor units compared to faster motor units, or central factors. Once the contribution of PAP has been exhausted, and larger motor units begin to fatigue, the time-history effect is decreased and the fatigue levels increase throughout the entire final cycle.

6.2.4 FINDINGS FROM REPETITIVE THUMB INTERPHALANGEAL FLEXION

Participants performed a repetitive thumb flexion task during one of four MVC-relative profiles. Each profile consisted of a series of “task” plateaus (ranging from 0-45% of MVC), paired with a “reference” plateau of 10% MVC. The profile orders were 0-10-15-10-30-10-45-10%, 15-10-45-10-0-10-30-10% MVC, 30-10-0-10-45-10-15-10% MVC, and 45-10-30-10-15-10-0-10% MVC.Overall, the order of force plateaus, within a cycle, had a small impact on the accumulation of fatigue during a task. All of the observed effects involving order occurred in the first cycle (of 5 total cycles). The effect of plateau order throughout the remaining cycles (2 to 5) was minimal. During the first cycle, twitch potentiation appeared to have a significant influence on the amount of voluntary force generated. The order that began with the highest force effort (45% MVC) produced a higher twitch during the very first plateau, compared to the order that began with the lowest force effort (0% MVC).

Once the second cycle began, all twitches appeared to become maximally potentiated, and the order effect no longer appeared to play an significant role. In cycles 3 through 5, the twitch force decreased, indicating fatigue was causing a reduction in force generation. With respect to an ergonomics application, there were no significant differences in fatigue level between orders at the end of each cycle. In 4 separate tasks, that consisted of different orders of the same required MVC-relative forces, fatigue accumulation was the same at the end of each cycle. In agreement with the results found in Chapter 3, this results contained in Chapter 4 support the hypothesis that potentiation is responsible for the increase in force generating capacity, but only during the initial phase of a fatiguing protocol.

6.2.5 IMPROVEMENT OF THE FATIGUE MODEL

The purpose of Chapter 5 was to validate and/or improve the 3CM by providing a series of experimental conditions that more closely reflected industrial work, compared to isotonic holding tasks.

6.2.5.1 EVALUATION OF COMPLEX PATTERNS

Optimizing the F and R coefficients, for both the $3CM_{GMU}$ and the $3CM_{OPT}$, resulted in predicted fatigue levels with an RMSD of less than 5% MVC when compared to experimental data. The RMSD between the experimental data and the $3CM_{XFL}$ was significantly higher (~30% MVC). The final fatigue values were slightly under predicted by the optimized models (-1.3% MVC for the $3CM_{GMU}$ and -2.4% MVC for the $3CM_{OPT}$). Conversely, the final fatigue value was substantially over predicted by the $3CM_{XFL}$, at 46.6% higher than experimental fatigue levels.

6.2.5.1 USE WITH ENDURANCE TIMES

Despite the accurate predictions of fatigue during complex MVC-relative patterns, the $3CM_{GMU}$ and $3CM_{OPT}$ models performed poorly when predicting experimental endurance times for isotonic tasks. The $3CM_{GMU}$ predicted an asymptote at 29% MVC, compared to 6.1% MVC seen with the $3CM_{XFL}$. The $3CM_{OPT}$ also produced poor predictions of endurance times, with an asymptote predicted at 49% MVC. One possible reason for this, is reperfusion of blood to the muscle, and flushing of metabolites in intermittent contractions (Zhang et al., 2004). This allows for greater recovery, but it is not represented in any capacity in any iteration of the 3CM.

6.3.0 APPLICATION AND FUTURE DIRECTIONS

Yung et al., (2013) found there were significantly different levels of fatigue when comparing MVC-relative patterns that had the same average force level, but presented the force time-histories in mechanically variant patterns. At that time, Yung et al., (2013) findings represented the only data regarding fatigue accumulation during tasks that were not either: 1) sustained at isotonic levels, or 2) switched on/off from a constant force level to complete rest. It was not possible to full validate a fatigue model with such simple effort patterns, as this does not represent what muscles, and muscle groups, experience in the workplace. To address this issue, the current thesis, along with the remaining studies that were used to validate the $3CM_{GMU}$, added 9 conditions that featured more industrial relevant force profiles, which could be used in the future to validate other fatigue models (Appendix D).

Multiple reviews have been performed to examine the applicability of fatigue models for use in digital human models (DHMs) (Berlin and Kajaks, 2010; Brouillette et al., 2012; Rashedi and Nussbaum, 2014). In all reviews, the 3CM was noted as a possible candidate for inclusion into DHMs. While the 3CM has been validated using endurance times at varying joints, it has been validated for more occupationally relevant force production patterns. The work from this thesis allows the modified $3CM_{GMU}$ to be considered for inclusion in DHMs.

While the MAE equation and the $3CM_{GMU}$ can both be used to analyze repetitive work, the results from the analyses produce different answers. Given a single task performed repetitively, the MAE equation will determine if a task is acceptable or not. If the effort level of the task performed is greater than the MAE level at a given duty cycle, the task is deemed to be unacceptable.

The $3CM_{GMU}$ can analyze multiple tasks repetitively, however, the acceptability of the task is not immediately determined. Instead, the current strength level can be compared against known rested strength data to determine the instantaneous force decline (ie. fatigue). Currently, Jack Digital Human modelling software (Siemens Corporation, Ann Arbor, MI) uses the task simulation builder to generate a fatigue report, which determines if there is sufficient rest allowance based on Rohmert's equation (Rohmert, 1973). As previously stated, the Rohmert Rest allowance is severely limited. The $3CM_{GMU}$ can aide in determining the fatigue that would result from a combination of multiple tasks, or the potential benefits of redistributing rest breaks within a cycle. Both the $3CM_{GMU}$ and MAE equation would be very beneficial for ergonomists when assessing repetitive work. Given the results from this thesis, these tools can confidently be applied to either single or multiple submaximal tasks completed repetitively. However, the coefficients used to do this with the 3CM would not also be appropriate for sustained, endurance contractions (which are not common in the workplace).

6.3.1 USE IN DIGITAL HUMAN MODELS

One of the most exciting potential applications of the $3CM_{GMU}$ is its ability to determine the cumulative effects of multiple tasks. Currently, most ergonomics tools can only evaluate isolated tasks. By its nature, the model can evaluate any combination of tasks and this should substantially widen the spectrum of occupational tasks that can be analyzed. For the first time, this will provide quantitative evidence to support the need to redesign, where applicable, for even the most complex tasks. To facilitate this further, the Jack DHM has recently implemented an ergonomics output report as part of their task simulation builder (Jack 8.2). A series of tasks can be modelled, and the demands on various joints of the body can be output as a function of load and posture over the entire time-history of the task. To determine the MVC-relative force requirement history of a task, for a particular target population, the absolute joint demands can be divided by the joint strengths, giving a percentage of maximum at any point of time. This can then be used to provide a target load for the $3CM_{GMU}$. For example, a task was simulated that consisted of a 50^{th} percentile female mannequin performing a simulated automotive seating assembly job. The worker used a ratchet to fasten a bolt (Figure 6.2 A), and then manually seated a Velcro fastener on the seat back (Figure 6.2 B). The worker then raised an electrical harness package into position, under the front of the seat pan (Figure 6.2 C). This was followed by the worker retrieving a plastic housing (Figure 6.2 D), and then fixed to the base of the car seat (Figure 6.2 E) (https://vimeo.com/111041234 to view as a video). This cycle was assumed to take one minute to complete, and was repeated 180 times over one hour of work. At the end of the task, the $3CM_{GMU}$ predicted that the right wrist would be at 76.3% of its rested flexion/extension strength (ie.

23.7% fatigued) (Figure 6.2), compared to 1.0% fatigued in the right elbow, and 13.3% fatigued about the right shoulder ab/adduction axis.

After this, using a theoretical ergonomic intervention, the demands of the task were reduced by 15% (bringing the 75% MVC demand down to 59.5% MVC) for all tasks in the cycle. Subsequently, the fatigue levels were decreased to 15.3% MVC for the wrist, 0.7% MVC for the elbow, and 8.3% MVC for the shoulder (Figure 6.2).

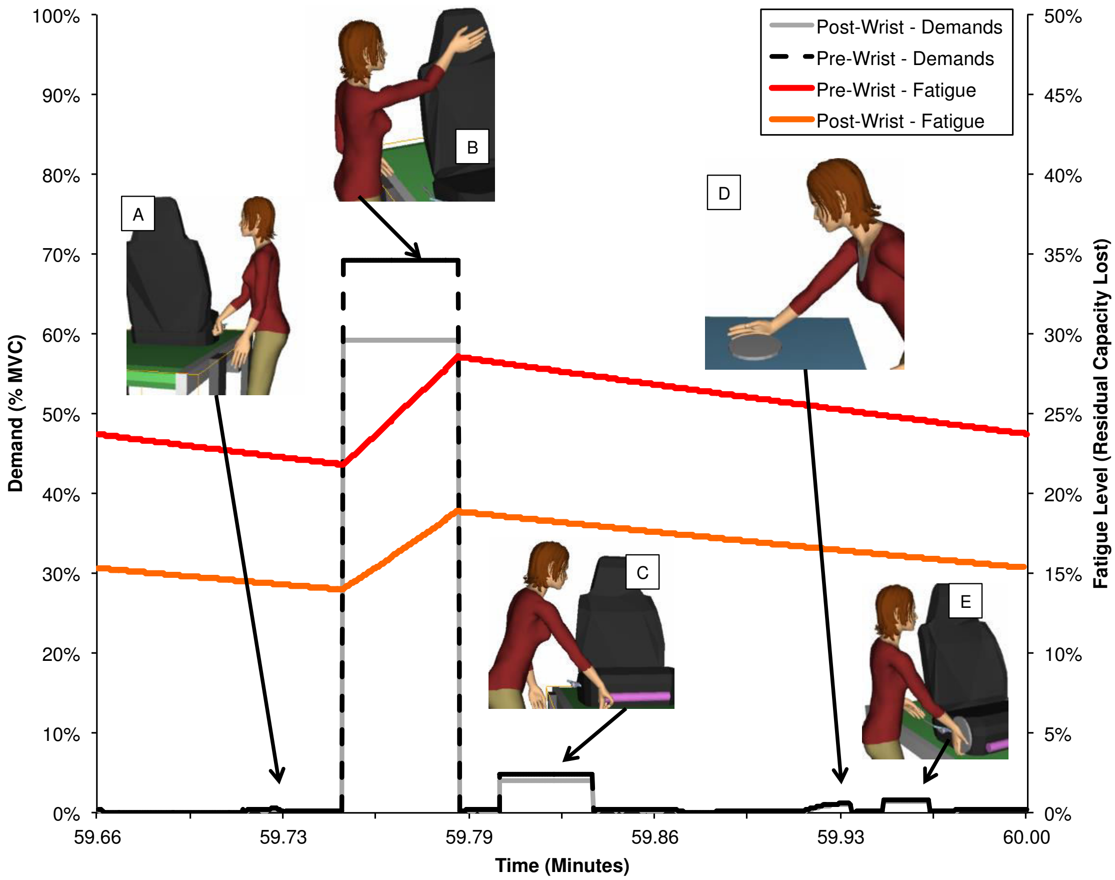

Figure 6.2. A time-history of demands for the right wrist (flexion/extension) from a simulated automotive assembly task. The demands were calculated and divided by the joint strength in Jack 8.2 (Siemens, Ann Arbor, MI) to provide a target load, which was modelled in the $3CM_{GMU}$. The task was simulated, before (Pre) and after (Post) a 15% reduction of task forces, to determine the impact of reducing the physical demands on the level of fatigue. One hour of work was simulated. The figure represents the final cycle of the hour of work. This process could be used proactively to determine the impact of ergonomics interventions.

The level of fatigue indicates the decrease in force generating capacity. An example from Peebles and Norris, (2003) was used in Potvin (2012) to show how the MAE equation could be applied to known force data, to assess what the maximum acceptable force would be at a given duty cycle. Similarly, known strength data generated from Jack could also be used to illustrate the effects of fatigue, and the consequent maximum force, which could be generated in a given posture. For example, in the simulated task from Figure 6.2, a medial push occurs against the back of the seat to set the Velcro (Figure 6.2 A). At that instant in time, Jack predicts a strength of 6.74 Nm. After the simulation, the predicted strength is 76.3% of the rested level (fatigue = 23.7%). The maximum force generating capacity at that instant would be predicted to be 6.74 Nm * 0.763 = 5.14 Nm.

The combination of the Jack DHM, along with the ergonomic report output and the $3CM_{GMU}$, provides a method of assessing repetitive work consisting of multiple tasks, and determining the reduction of force generating capacity. However, reduced force-generating capacity is not the only negative outcome of muscle fatigue. Muscle fatigue can lead to impairment of movement quality (such as smoothness of motion, repeatability of end goals of motion, and precision (Hogan, 1991). Also, work performance (Gates and Dingwell, 2008), and quality of work (Dan et al., 2010; Lin et al., 2001; Wartenberg et al., 2004) have both been shown to be impacted as a result of fatigue in the workplace. However, it is unknown what level of fatigue is associated with significant decreases in worker productivity or work quality. In numerous ergonomics tools, there are threshold limit values, which determine the acceptability of a job task (Garg et al., 1978; McAtamney and Corlett, 1993; Potvin, 2012; Sonne et al., 2012). These limits provide an ergonomist with standards to guide decisions regarding whether a job requires administrative controls (eg. a new policy) or engineering controls (eg. a physical redesign). Future work should aim to simulate repetitive jobs with and without quality issues; provide predicted fatigue levels, and determine if there is a threshold limit of fatigue that is related to these other detrimental outcomes.

6.4.0 LIMITATIONS

6.4.1 CENTRAL FATIGUE DURING FORCE PRODUCTION

Maximum voluntary forces are produced as a result of many factors. Muscle fatigue can decrease the level of force production by impairing the ability of cross bridges to form through an accumulation of metabolites or sarcoplasmic calcium (Allen et al., 2008). This type of fatigue, which occurs beyond the neuromuscular junction, is known as peripheral fatigue. However, central fatigue can also occur, and is a result of decreased activity from the motor cortex which may be due to decreased motivation, pain, or other inhibition (Gandevia, 2001). These central factors can be significantly influenced by external factors, such as psychosocial stressors (Marras et al., 2000), or the presence of music (Stork et al., 2014). As a result, if these central factors are not controlled, it can be difficult to clearly interpret the level of muscle fatigue manifested during an experimental trial, or in a workplace. During a maximum voluntary contraction, the force produced by an individual is a factor of both peripheral and central factors. An increase in these central factors, such as increased stress due to supervision (Marras et al., 2000), can lead to increased inhibition, and decreased force production. The experiments in this thesis (and particularly in Chapters 3 and 4) focused on evaluating fatigue as a factor of a decrease in maximum voluntary force. While integrating both types of fatigue into the validation of the fatigue model produces a representative level of fatigue at any time during a trial, it does not partition the fatigue levels into central or peripheral components. Further work should focus on determining the relative contribution of central fatigue, and creating a modification to the $3CM_{GMU}$, which can increase or decrease the fatigue level based on centrally contributing factors.

6.4.2 APPLYING THE MODEL TO LIFTING/LOWER, OR OTHER BODY PARTS

The MAE equation was created using psychophysical data collected during experiments involving repetitive work of the upper extremities. Similarly, the experiments used to validate the $3CM_{GMU}$ focused on fatigue in the muscles of the forearm and hand. However, fatigue and recovery rates are clearly influenced by body part (Frey Law and Avin, 2010; Fukutani et al., 2012). As a result, the findings from all chapters in this thesis should only be considered to apply to tasks involving the muscles of the hand and forearm. Future work should focus on validating the MAE equation and the 3CM for other regions of the body, particularly the muscles associated with lifting and lowering.

6.4.3 AGING POPULATION

The effect of an aging work force has become an ever more prevalent question in ergonomics. The physical changes that occur with age impact how muscles fatigue and recover during bouts of exercise. These changes include increases in intramuscular fat, decreases in the quantity of motor units, and a lost of fast twitch fibres (Deschenes, 2004). As a result, there are a higher proportion of slow twitch fibres in an older individual. This results in increased fatigue resistance and greater endurance (Hodder et al., 2014) for the same relative load, but also lower absolute force production capacity. The population used in this thesis (university aged females), would have significantly different muscle composition, resulting in a different fatigue pattern compared to an older individual. Future research should aim to determine how the effects of age impact fatigue accumulation in complex force histories.

6.4.4 GENDER DIFFERENCES

The population recruited for this study consisted of university-aged females. In the manufacturing sector in 2009, females composed 30.1% of the workforce (Ferrao, 2010). Males and females have significantly different physical compositions, which result in significantly different fatigue and recovery rates. Males are typically have higher maximum power output compared to females, but are also less fatigue resistant and recovery more slowly (Glenmark et al., 2004). These differences may be primarily due to differences in muscle fibre composition (Wüst et al., 2008), but also muscle mass, muscle metabolism and voluntary activation patterns (Billaut and Bishop, 2009). Future research in this field should include male participants, to more accurately represent the manufacturing industry population.

6.4.5 OBESITY

Finally, the mean BMI of participants in this thesis was considered to be normal (BMI = 22.4, with an average height of 166.3 cm, and weight of 61.7 kg). However, 24.3 – 25.4 % of the Canadian population is Obese (Canadian Institute for Health Information, 2011). Obese individuals have been shown to produce less force, and have greater force losses compared to non-obese individuals (Maffiuletti et al., 2007). Obesity can influence the fatigue process by increasing demand on the central nervous system to counteract gravity in obese individuals (Allen et al., 2008). The experiments in this thesis could be redone using a different population consisting of obese and non-obese participants to determine the effects of fatigue in this population.

6.5.0 GENERAL CONCLUSION

This thesis aimed to validate two tools that could be used by ergonomists to assess repetitive work. In addition, empirical data were collected for fatigue accumulation during a number of complex MVC-relative patterns. In Chapter 2, the MAE equation (Potvin, 2012) was shown to provide accurate predictions of acceptable efforts for duty cycles greater than 0.5 – which had previously not been established. In Chapter 3, the history of efforts was shown to influence fatigue accumulation during a complex MVC-relative pattern. In Chapter 4, the fatigue accumulation in the beginning phase of a task was confirmed to be a result of post-activation potentiation. However, the order of forces within a cycle did not play a role in fatigue accumulation. Finally, the $3CM_{GMU}$ provided accurate predictions of fatigue during complex MVC-relative profiles. It also provided accurate endurance time predictions for sustained efforts of greater than 30% MVC.

The MAE equation and the $3CM_{GMU}$ are two tools can be used by ergonomists to assess repetitive tasks. Future work should aim to develop a fatigue model capable of assessing both complex intermittent tasks and sustained isotonic endurance tasks. Additional work (using both fatigue models and experimental data) should provide a method of using the MAE equation for jobs consisting of multiple tasks. Finally, the influence of central fatigue should be further explored, so it can be included in future models of muscle fatigue prediction.

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Appendix A: Ethics approval for Chapter 2

McMaster University Research Ethics Board (MREB)
FACULTY/GRADUATE/UNDERGRADUATE/STAFF
APPLICATION TO INVOLVE HUMAN PARTICIPANTS IN RESEARCH
[Behavioural / Non-Medical]

Date:	**Application Status: New [X] Change [ ]**	**Protocol #:**

Helpful Hints **Mouse over bold blue hypertext links for help with completing this form.**

Please refer to the McMaster University < Research Ethics Guidelines and Researcher's Handbook >, prior to completing and submitting this application.
If you have questions about, or require assistance with, the completion of this form, please contact the Ethics Secretariat at ext. 23142, or 26117 or ethicsoffice@mcmaster.ca

HOW TO SUBMIT:
If you are submitting hard copies of your typewritten application send this form and all accompanying material in duplicate (2 copies) to the Ethics Secretariat at the address below.
If submitting by e-mail, send your typewritten application plus attachments, and forward the original signed signature page to the **Ethics Secretariat, Research Office for Administration, Development and Support (ROADS), Room 305 Gilmour Hall, ext. 23142**, **ethicsoffice@mcmaster.ca**.

If you intend to change a previously cleared protocol, please submit the "**< Change Request >**" form.

SECTION A – GENERAL INFORMATION
1. Study Titles: (Insert below)

TITLE: Psychophysical determination of acceptable efforts during high duty cycle tasks
(a): **Title:** (If different from above i.e. the grant title.)

2. **Investigator Information:** **This form is not to be completed by < Faculty of Health Science researchers > .**

	Full Name	**Department** *& or name of university if different from McMaster*	**telephone number(s)** *& Extension*	**E-mail address** (*Address you regularly use)*
Principal Investigator*	Jim R. Potvin	Kinesiology	X23004	potvinj@mcmaster.ca
Student Investigator(s)*	Michael Sonne	Kinesiology	NA	sonnemw@mcmaster.ca
Faculty Supervisor(s)*	Jim R. Potvin	Kinesiology	X23004	potvinj@mcmaster.ca

***Faculty and staff, information should be inserted above the black bar in this table. Student researcher and faculty supervisor information should be inserted below the black bar in this table.**

3. **Start dates and end dates:** *(Contact the Ethics Secretariat at X 23142 or ethicsoffice@mcmaster.ca for urgent requests.)*
(a) **What is the date you plan to begin recruiting participants or obtain their permission to review their private documents?**

December 1st, 2012

(b) **What is the estimated completion date for data collection with human participants?**

February 28, 2013

N:/ethics/forms/MREBForm.docx
- 1 -

Appendix B: Ethics - Informed Consent for Chapter 3

January 21, 2013

Letter of Information and Consent

Predicting Fatigue Accumulation During Complex Intermittent Tasks

Principal Investigator: Dr. James Potvin
Department of Kinesiology
McMaster University,
Hamilton, Ontario, Canada
(905) 525-9140 ext. 23004;
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Student Investigators: Nicholas LaDelfa (ladelfn@mcmaster.ca), Michael Sonne (sonnemw@mcmaster.ca), Kayla Fewster (fewstek@mcmaster.ca), Jessica Cappelletto (cappelja@mcmaster.ca), Ryan Wells (wellsrw@mcmaster.ca), Ebram Ibrahim (ibrahe@mcmaster.ca), Natalie D'Isabella (disabent@mcmaster.ca), Pat Dang (dangp@mcmaster.ca)

Purpose of the Study
We will be measuring the changes in strength as you perform a series of contractions between 10% and 60% of your maximum strength. These trials will be conducted with your elbow flexors, knee extensors and hand grip muscles. We will also be measuring the muscle activity in your muscles with electrodes that will be adhered to the skin. The purpose of the research is to better understand how complex task demands contribute to the accumulation of fatigue in skeletal muscles.

Procedures involved in the Research
After being shown the equipment and electrodes, we will record your height, weight and age. Surface electrodes will then be stuck to the skin over the muscles of interest. For the elbow flexion trials, the muscles will be the biceps (elbow flexors), triceps (elbow extensors) and some forearm muscles (elbow flexors) and you will be seated with your elbow at 90 degrees. Your wrist will be secured as shown in Figure 1. For the knee extensor trials, the muscles will be the quadriceps (knee extensors), hamstrings (knee flexors) and calf muscles (knee flexors) and you will be seated in a dynamometer with your ankle secured as shown in Figure 2. For the hand grip trials, the muscles will be the forearm flexors (front of forearm) and forearm extensors (back of your forearm) and you will grip a force gauge as shown in Figure 3. You will be asked to perform a series of contractions at levels between 10% and 60% of your maximum for periods of time ranging from 20 to 30 seconds. After each exertion, you will be asked to perform a brief maximum contraction. This will proceed until you can no longer maintain one of the required force levels for the required time. Each session should not exceed 1 hour.

Potential Harms, Risks or Discomforts:
You may experience local muscle soreness in the muscles involved in the exertions. You will be asked to maintain a contraction until muscle exhaustion or your rating of perceived discomfort reaches a score of 7 out of 10 (a 6 is rated as "definitely uncomfortable sensations" and 8 is "very uncomfortable sensations").. This muscle soreness, which is typical of any physical exertion study, will be similar to moderately strenuous exercise and should not last longer than 24 hours. You can end the trial whenever you feel excessive discomfort or pain. Although very rare, you may feel some redness or itchiness from the adhesive that keeps the electrode in place on your arm. If pain in the arm persists longer than 48 hours, it may be useful to consult a family physician.

Appendix C: Ethics Approval for Chapter 4

Hamilton Health Sciences | McMaster University — Inspiring Innovation and Discovery | St. Joseph's Healthcare Hamilton

Hamilton Integrated Research Ethics Board (HIREB)
293 Wellington St. N., Suite 102, Hamilton, ON L8L 8E7
Telephone: 905-521-2100, Ext. 42013
Fax: 905-577-8378

January 21, 2014

PROJECT NUMBER: **13-710**

PROJECT TITLE: Fatigue and recovery in peripheral musculature during a task with a complex force time-history

PRINCIPAL INVESTIGATOR: **Dr. Jim Potvin**

This will acknowledge receipt of your email on January 14, 2014 which enclosed revised copies of the Information/Consent Form, Email Script and the Application Form along with response to the additional queries of the Board for the above-named study. These issues were raised by the Hamilton Integrated Research Ethics Board at their meeting held on November 6, 2013. Based on this additional information, we wish to advise your study has been given ***final*** approval from the full HIREB.

The following documents have been approved on both ethical and scientific grounds:

- The submission
- Study Protocol
- Information/Consent Form version dated January 8, 2014
- Recruitment Flyer
- Email Script

Please note attached you will find the Information/Consent Form and the Recruitment Flyer with the HIREB approval affixed; all consent forms/recruitment flyers used in this study must be copies of the attached materials.

We are pleased to issue final approval for the above-named study for a period of 12 months from the date of the HIREB meeting on November 6, 2013. Continuation beyond that date will require further review and renewal of HIREB approval. Any changes or revisions to the original submission must be submitted on an HIREB amendment form for review and approval by the Hamilton Integrated Research Ethics Board.

PLEASE QUOTE THE ABOVE-REFERENCE PROJECT NUMBER ON
ALL FUTURE CORRESPONDENCE

Sincerely,

Dr. Raelene Rathbone
Chair, Hamilton Integrated Research Ethics Board

The Hamilton Integrated Research Ethics Board operates in compliance with and is constituted in accordance with the requirements of: The Tri-Council Policy Statement on Ethical Conduct of Research Involving Humans; The International Conference on Harmonization of Good Clinical Practices; Part C Division 5 of the Food and Drug Regulations of Health Canada, and the provisions of the Ontario Personal Health Information Protection Act 2004 and its applicable Regulations; for studies conducted at St. Joseph's Hospital, HIREB complies with the health ethics guide of the Catholic Alliance of Canada

Appendix D: Summary of Experimental Fatigue Values

The fatigue level (percent decrease in MVC force) is shown for all experimental data (n = 9) used to evaluate and/or develop the $3CM_{XFL}$, $3CM_{OPT}$, and $3CM_{GMU}$. Fatigue levels after the first MVC are in red, and final fatigue levels are in blue. The time (in green) is when each MVC happened during the first cycle of each task.

Study					
D'Isabella, Hodder, Sonne & Potvin (2013)	**Time (s)**	16	32	48	64
	Plateau (% MVC)	0%	10%	20%	10%
	Cycle 1	-0.6%	7.7%	8.1%	15.1%
	Plateau (% MVC)	40%	30%	10%	20%
	Cycle 2	18.0%	21.2%	21.5%	24.0%
	Plateau (% MVC)	40%	20%	30%	40%
	Cycle 3	30.1%	23.8%	30.6%	33.4%
	Plateau (% MVC)	10%	40%	10%	20%
	Cycle 4	31.2%	36.8%	32.4%	33.8%
	Plateau (% MVC)	30%			
	Cycle 5	36.0%			

Study						
Dang (2013)	**Time of MVC (s)**	16	32	48	64	80
	Plateau (% MVC)	0%	20%	10%	30%	10%
	Cycle 1	0.9%	2.7%	4.5%	7.7%	9.7%
	Cycle 2	7.0%	10.0%	10.6%	14.7%	14.1%
	Cycle 3	15.5%	14.0%	15.5%	19.0%	18.0%
	Cycle 4	20.3%	17.0%	23.2%	23.9%	25.7%

Study							
Sonne, Hodder, Wells & Potvin (2014)	**Time (s)**	21	42	63	84	105	126
	Plateau (% MVC)	0%	15%	30%	45%	30%	15%
	Cycle 1	-2.3%	1.4%	8.7%	12.1%	15.7%	10.6%
	Cycle 2	6.3%	11.9%	15.5%	26.0%	23.8%	19.8%
	Cycle 3	15.9%	25.0%	29.2%	40.4%	35.9%	33.2%

Study									
Whittaker (2014) (Front Load)	**Time of MVC (s)**	16	48	80	112	144	176	208	240
	Plateau (% MVC)	0%	15%	25%	15%	35%	15%	45%	15%
	Cycle 1	5.5%	6.0%	6.1%	7.4%	4.8%	8.1%	11.8%	13.8%
	Cycle 2	5.4%	5.4%	4.9%	8.3%	10.2%	10.8%	13.3%	15.9%
	Cycle 3	6.8%	8.1%	11.7%	14.4%	16.3%	17.0%	17.6%	21.7%
	Cycle 4	7.8%	9.8%	12.1%	14.4%	18.6%	19.7%	20.4%	20.9%
	Cycle 5	15.6%	14.0%	18.2%	19.0%	18.0%	21.5%	24.0%	25.8%

Study									
Whittaker (2014) (Even Load)	**Time of MVC (s)**	16	48	80	112	144	176	208	240
	Plateau (% MVC)	0%	15%	25%	15%	35%	15%	45%	15%
	Cycle 1	7.5%	9.3%	8.5%	9.5%	8.9%	9.8%	9.8%	9.3%
	Cycle 2	13.2%	10.2%	12.1%	13.3%	10.6%	11.0%	13.9%	12.3%
	Cycle 3	14.6%	13.8%	12.6%	16.3%	17.2%	18.9%	16.1%	18.4%
	Cycle 4	20.4%	17.0%	15.5%	14.6%	19.5%	17.8%	16.8%	20.7%
	Cycle 5	24.8%	21.4%	17.3%	17.1%	20.0%	22.1%	20.0%	22.8%

Study									
Sonne, Chapter 4 Order 0-15-30-45	**Time of MVC (s)**	18	36	54	72	90	108	126	144
	Plateau (% MVC)	0%	10%	15%	10%	30%	10%	45%	10%
	Cycle 1	2.9%	11.2%	8.5%	11.1%	11.7%	14.5%	15.1%	15.5%
	Cycle 2	16.3%	14.4%	15.9%	17.3%	17.7%	22.2%	21.7%	25.4%
	Cycle 3	19.8%	19.8%	19.3%	22.5%	21.4%	23.6%	24.0%	25.2%
	Cycle 4	25.4%	22.6%	21.4%	21.7%	25.5%	25.7%	27.8%	26.4%
	Cycle 5	25.6%	23.0%	25.3%	25.4%	27.3%	24.1%	32.2%	26.4%

Study									
Sonne, Chapter 4 Order 15-0-45-30	**Time of MVC (s)**	18	36	54	72	90	108	126	144
	Plateau (% MVC)	15%	10%	45%	10%	0%	10%	30%	10%
	Cycle 1	8.1%	9.0%	11.2%	15.9%	12.3%	15.5%	18.0%	22.4%
	Cycle 2	17.5%	18.4%	20.6%	19.4%	20.2%	20.7%	23.4%	22.4%
	Cycle 3	25.0%	26.0%	27.7%	28.8%	21.6%	24.3%	26.1%	30.2%
	Cycle 4	27.2%	27.5%	28.9%	30.6%	28.6%	26.8%	28.6%	27.8%
	Cycle 5	30.2%	30.5%	33.2%	34.7%	35.3%	33.6%	33.6%	32.3%

Study									
Sonne, Chapter 4 Order 30-45-0-15	**Time of MVC (s)**	18	36	54	72	90	108	126	144
	Plateau (% MVC)	30%	10%	0%	10%	45%	10%	15%	10%
	Cycle 1	6.7%	11.1%	11.1%	13.4%	18.6%	18.2%	17.0%	17.7%
	Cycle 2	20.6%	20.2%	21.4%	20.2%	23.1%	22.7%	22.2%	23.5%
	Cycle 3	26.0%	24.3%	24.9%	23.2%	27.5%	26.4%	24.4%	26.1%
	Cycle 4	27.1%	27.1%	24.4%	23.9%	28.5%	29.0%	28.9%	27.7%
	Cycle 5	29.8%	30.9%	27.8%	25.5%	29.4%	30.9%	30.2%	29.4%

Study									
Sonne, Chapter 4 Order 45-30-15-0	**Time of MVC (s)**	18	36	54	72	90	108	126	144
	Plateau (% MVC)	45%	10%	30%	10%	15%	10%	0%	10%
	Cycle 1	10.8%	18.5%	18.2%	18.8%	19.4%	23.9%	17.8%	19.0%
	Cycle 2	21.3%	19.2%	22.0%	21.9%	17.8%	21.8%	22.3%	18.2%
	Cycle 3	22.8%	27.4%	24.5%	25.4%	26.8%	24.3%	25.0%	24.2%
	Cycle 4	25.9%	23.7%	26.7%	28.9%	26.2%	30.0%	28.6%	26.0%
	Cycle 5	25.5%	30.0%	29.5%	26.7%	28.4%	29.6%	28.4%	23.6%